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Satellite Navigation Backup Study

Final Report

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EXECUTIVE SUMMARY

Introduction and Objectives

The Joint Planning and Development Office (JPDO) manages a unique public/private partnership in developing a sweeping vision that will guide the evolution of the National Air Space (NAS) to meet the needs of the 21st century. This initiative, called the Next Generation Air Transportation System (NextGen), will bring transformation to the U.S air transportation system by 2025. A key capability for transforming the NAS is satellite-based navigation (SatNav). Modernization plans and augmentation strategies for the Global Positioning System (GPS) will make it a more valuable asset to aviation. The addition of Galileo and possibly GLONASS and COMPASS will further enhance the performance capabilities of satellite based navigation systems.

The vulnerabilities of GPS as a navigation signal are well known and the threat of disruption to this service is a concern. These vulnerabilities, defined in technical reports such as the 2001 Volpe GPS Vulnerability Assessment report[1];US policies to support critical transportation applications in the event of a GPS disruption; and the importance of SatNav in the JPDO vision are the motivations for this study to identify and assess backup satellite navigation solutions. Specifically, the objective of this SatNav Backup Study is to identify an appropriate set of "area navigation"[2] satellite backup solutions for operation in the NextGen in 2015, 2020, and 2025. The study includes a requirements analysis for a backup system, development of evaluation criteria, and a comparative cost assessment for each proposed backup solution, supporting the overall evaluation of candidate solutions.

A secondary focus of the study was consideration of possible candidates for SatNav backup to support the precision approach and surface navigation phases of flight operations. This aspect of the study is presented in the appendices.

Methodology Overview

Due to the large number of stakeholders within the aeronautical environment, each with differing needs and desires, decision making can be challenging. There was a desire to implement a methodology for this study that was process-oriented, accommodated multi-criteria decisions, and employed customer views and perspectives. To meet these desires, an approach based on a standardized methodology for decision making (used in business improvement processes such as Six-Sigma) was defined. Specifically, this study employed an approach that is a tailored implementation of the Analytical Hierarchy Process. This methodology is shown in Figure ES-1.

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[1] DOT Volpe Report: *Vulnerability Assessment of the Transportation Infrastructure Relying on the Global Positioning System*, Final Report, John A. Volpe National Transportation Systems Center, August 29, 2001.
[2] This study uses the term 'area navigation' to include en route, terminal, and non precision approach phases of flight operation.

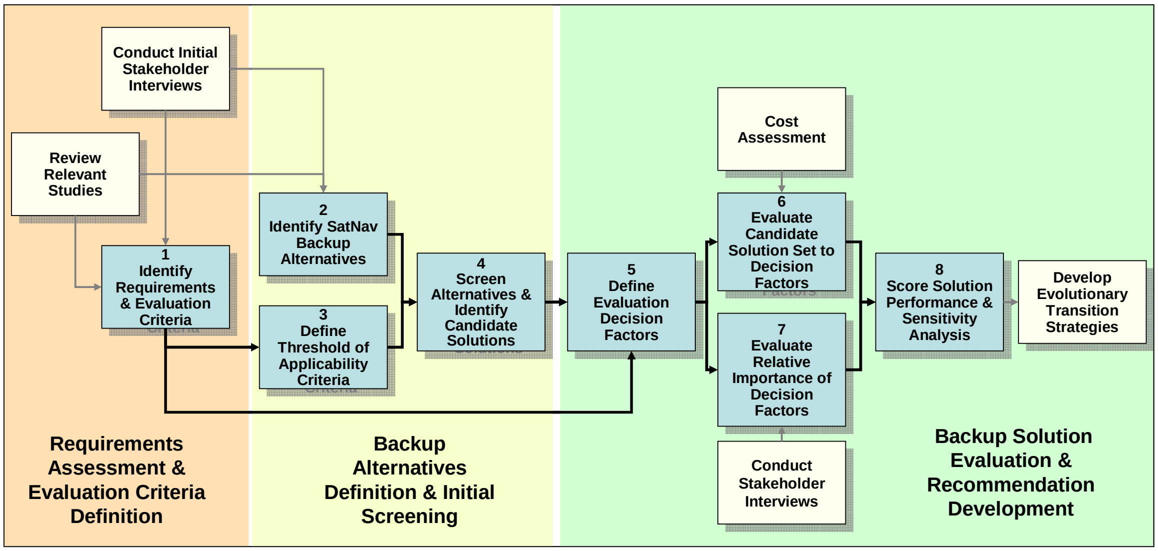

Figure ES-1: SatNav Study Methodology

In the figure above, the workflow is organized into three major sequential activities: *Requirements Assessment and Evaluation Criteria Definition*; *Backup Alternatives Definition and Initial Screening*; and *Backup Solution Evaluation and Recommendation Development.* The major tasks associated with each of these activities is noted below:

- *Requirements Assessment and Evaluation Criteria Definition:* Includes identification of requirements/desirable features for SatNav backup solutions based on review of published requirements; operating concepts and applicable policies; and stakeholder interviews, and then translating these requirements/desirable features into evaluation criteria
- *Backup Alternatives Definition and Initial Screening:* Includes identification of a preliminary set of alternative candidates for providing SatNav backup capabilities; selection of critical threshold criteria to allow an initial screening of the preliminary candidates; and applying the threshold criteria to select a smaller set of the most suitable candidates for further consideration
- *Backup Solution Evaluation and Recommendation Development*: Includes evaluation of candidate solutions against the remaining criteria (those not applied in the screening process); weighting the evaluation criteria based on stakeholders inputs; and identifying most preferable/highest scoring backup solutions based on evaluation results. These results support the development of SatNav backup solution recommendations.

Requirements Assessment and Evaluation Criteria

A preliminary focus of the *Requirements Assessment and Evaluation Criteria Definition* activity was the review of applicable source documents to serve as an input to a functional assessment of the required capability for a backup solution. This work also included interviews with stakeholders to identify evaluation considerations relevant from their perspective and system needs, and a determination of the future operational environment for navigation systems and its associated impact on needs and capabilities.

Based on the review of applicable requirements and concepts and upon an initial set of interviews with stakeholders, a list of factors for consideration in the backup system assessment was developed, as shown in Table ES-1.

Table ES-1: Factors for Consideration in SatNav Backup System Assessment

Requirements and Desired Capabilities	
Technical Requirements	≤ RNP-2.0 for en route
	≤ RNP-1.0 for terminal area
	RNP-0.3 for non precision approach (NPA)
Functional Requirements and Capabilities	Technical readiness in 2015-2025
	Backup system must be independent of and not reliant on GNSS.
	Seamless failover for aircraft
	Seamless failover for air traffic control
	Navigate through terminal area SatNav disruption maintaining RNP-1.0 to the approach (minimum)
	Navigate through terminal area SatNav disruption maintaining RNP-1.0 to the approach and perform a RNP-0.3 NPA
	Low user life cost (desired characteristic)
	Low infrastructure provider life cost (desired characteristic)
	Near global support (goal)
	Available, reliable, small size & weight
	Safe transitions between primary and back-up operations
	Support area navigation (latitude, longitude) like GPS
	Minimize radio spectrum requirements
	A SatNav backup must sustain aircraft operations for an extended period of time.
	The backup strategy should support navigation needs for all segments of transportation and other US PNT needs as well.

To support application of the evaluation criteria in this assessment, the factors noted above were organized into a hierarchical structure. This provides a means to identify unique sets of criteria and meaningful groups for which the relative importance between the groups of criteria can be assessed. Each group of criteria makes up a branch of what is called the *decision factor hierarchy*, where the group/branch names are called global (or Level-1) evaluation decision factors. The organization of the criteria derived above into a decision factor hierarchy applied in this study is shown in Figure ES-2.

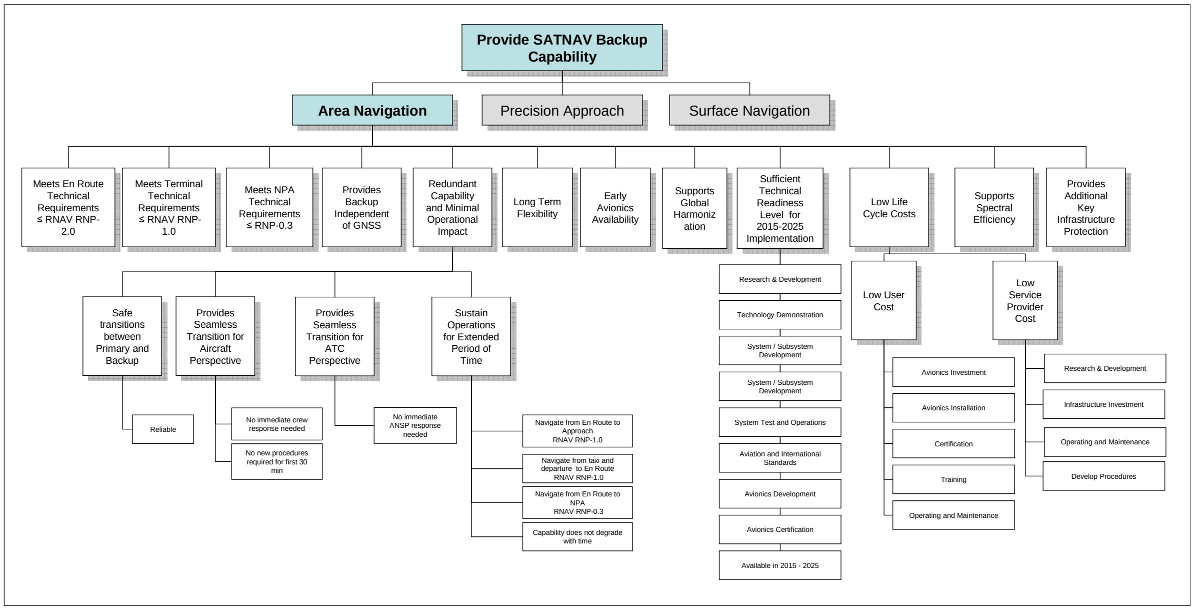

Figure ES-2: SatNav Backup Study Decision Factor Hierarchy

The top-level evaluation decision factors in the figure above were used to screen alternatives (to identify applicable candidates) and to perform a relative assessment of candidates to identify those most preferable/applicable for meeting the needs of a SatNav backup solution (described below).

Backup Alternatives Definition and Initial Screening

The first step in the screening task was the identification of applicable SatNav alternatives for consideration. The candidates considered in this study were defined based on several sets of inputs. These included NGATS Institute mandates; stakeholder inputs (from a first set of stakeholder interviews); and study team additions based on review of applicable concepts and studies. The full set of alternatives in this study included:

- **DME/DME/INS:** An approach where DME signal inputs from multiple ground DME Navaids are used to derive position; the inertial capability allows the system to coast when a position determination from ground DME Navaids is not available
- **eLORAN:** An approach where eLORAN signal inputs from multiple ground eLORAN transmitters are used to derive position
- **GNSSS/INS:** An approach where an inertial capability allows a GNSS system to coast when position information from a GNSS system is not available
- **VOR:** An approach where VOR azimuth determinations relative to ground transmitter locations are used to derive position
- **Hardened GNSS system:** An approach that considers modification to the GNSS capability to address threats associated with intentional or unintentional interference sources
- **Terrain reference navigation:** An approach where users estimate position based on a best match between measured surface features and a terrain database

- **Multilateration system:** an approach where aircraft periodically send signals that are received at several ground locations that determine aircraft position by the time difference of arrival principle; calculated positions are then transmitted back to the aircraft

The next step in the screening process was to define a subset of the evaluation criteria to define a threshold of applicability and screen alternatives to identify viable candidates for further consideration. To select the threshold criteria, criteria were grouped into three applicability categories as follows:

- Essential (Level 1)
- Strongly preferred (Level 2)
- Preferred (level 3)

All evaluation criteria associated with technical requirements were assigned to the Essential applicability category. The remaining criteria were assigned based on the functional/operational context and needs for a backup solution as well as initial preference/importance of criteria inferred from the first round of stakeholder interviews. The result of this organization of evaluation criteria is shown in Table ES-2.

Table ES-2: Ordering of Evaluation Criteria

Technical Requirements and Desired Capabilities		Criteria Level
Technical Requirements	≤ RNP-2.0 en route	(1)
	≤ RNP-1.0 terminal	(1)
	RNP-0.3 NPA	(1)
Functional Requirements and Capabilities	Technical readiness in 2015-2025	(1)
	Backup system must be independent of and not reliant on GNSS.	(1)
	Redundant capability and minimal operational impact	(2)
	Long term flexibility	(3)
	Low life cycle cost (desired characteristic)	(2)
	Global harmonization (goal)	(3)
	Early Avionics Availability	(3)
	Spectral Efficiency	(3)
	Additional Key Infrastructure Protection	(3)

The ≤ RNP-2.0 en route and ≤ RNP-1.0 terminal area requirements align with the projected minimum navigation performance requirements for performing operations in managed airspace. The RNP-0.3 requirement aligns with the navigation performance necessary to perform a non precision approach, a common runway approach procedure performed in instrument meteorological conditions. The requirement for technical readiness in 2015-2025 is derived from the Study Objective, that is, to identify candidate solutions at 2015, 2020, and 2025. The requirement that the backup must be independent of

and not reliant on GNSS allows the navigation system to continue to provide necessary guidance in the event of a disruption to GNSS and is based on National Policy to provide such backups.

All Level 1 criteria were identified as the threshold criteria and were applied in the alternatives screening process. The remaining evaluation decision factors were applied in a later part of analysis.

To perform the screening process, the ability of each of the identified SatNav backup alternatives to satisfy the threshold criteria was evaluated. Those candidates that had been validated to meet all of the threshold criteria were carried forward for further consideration in the backup solution assessment. These candidates included:

- DME/DME/INS
- GNSS/INS
- eLORAN

Backup Solution Evaluation and Recommendations

The three candidates brought forward from the screening process were assessed further with regard to the remaining evaluation criteria (those not applied in the screening process). One of these evaluation criteria was life cycle cost. A net present value cost model that considered key cost drivers and supported a relative assessment of candidate backup solutions was developed. This model provided rough order of magnitude estimates of costs that included initial investment (for new avionics and ground infrastructure build-out) and a fifteen year operations/maintenance period. Costs were estimated for the backup solution as a whole (considering the ground service provided and various navigation aircraft user categories) and individually for specific navigation system participants. To estimate costs in a uniform fashion, several assumptions regarding the backup solutions were applied. These included a build-out of ground infrastructure (where applicable) for equivalent airspace coverage in the U.S. and an assumption that all aircraft accounted for in the stakeholder user groups would equip. Assumptions of current avionics equipage based on published AOPA data were also applied. A summary of the overall costs results (considering all system participants collectively) is provided in Table ES-3.

Table ES-3: Summary of Cost Assessment Results

Candidate	Estimate Relative Costs	
	Approx Per User/ Per Site Investment	Preliminary NPV
DME/DME/INS	Aircraft: $32-62 K Ground: $1,150 K	$8185 M
GNSS/INS	Aircraft: $25-30 K Ground: $400 K	$4781 M
eLORAN	Aircraft: $22-42K Ground: $15,200 K	$4818 M

The cost estimates indicate that where aircraft have to equip, there are not significant differences among the candidate solutions. However, because there is wide variation in current equipage (e.g. most commercial jets have DME and INS, while many general aviation aircraft do not), there was a significant difference in life cycle costs for the different backup solutions. From the ground service provider perspective, the per-site ground investment varied significantly among candidate solutions. However, because of the varying number of site installations/upgrades required, the overall investment cost among candidate solutions was not as significant (ranges from approx. $100 M to $150 M) (not shown in the table above, but details provided within this report).

Life cycle costs was one of the seven evaluation criteria. Table ES-4 summarizes the complete list of evaluation criteria (decision factors) that are the Level 2 and 3 criteria from Table ES-2.

Table ES-4: Subset of Key Decision Factors/Evaluation Criteria with Definitions

Decision Factor	Description of Stakeholder Value
Low Life Cycle Costs	Values low life cycle costs to the users and the infrastructure provider to provide and maintain a SatNav backup system
Long Term Flexibility	Values flexibility in adapting to changing needs without significant reinvestments
Redundant Capability and Minimal Operational Impact (Seamless Failover)	Values near equivalent navigation performance to that of the primary Satellite Navigation system, and also that when required, the failover is seamless, with no exceptional crew or ground actions required
Early Avionics Availability	Values the early availability of avionics for the SatNav backup
Global Harmonization	Values the near global support of a determined SatNav backup
Spectral Efficiency	Values the efficient use of aeronautical radio spectrum
Additional Key Infrastructure Protection	Values that the SatNav backup system would also benefit other key aviation and national infrastructure Position, Navigation, and Timing (PNT) requirements

The assessment included the interviewing of stakeholders to provide a pair-wise comparison of the evaluation decision factors. Based on the comparison results, a stakeholder weighting of evaluation factors was computed. Identified stakeholders in this process included Air Carrier, General Aviation, Government and Standards Organizations, U.S. Stakeholders, European Stakeholders and Combined (all Stakeholder inputs). Overall, Redundant Capability and Minimal Operational Impact; Global Harmonization; Spectrum Efficiency; and Long Term Flexibility were identified by stakeholders as the four most important evaluation factors. The weighting results for the combined set of interviewed stakeholders is presented in Figure ES-3.

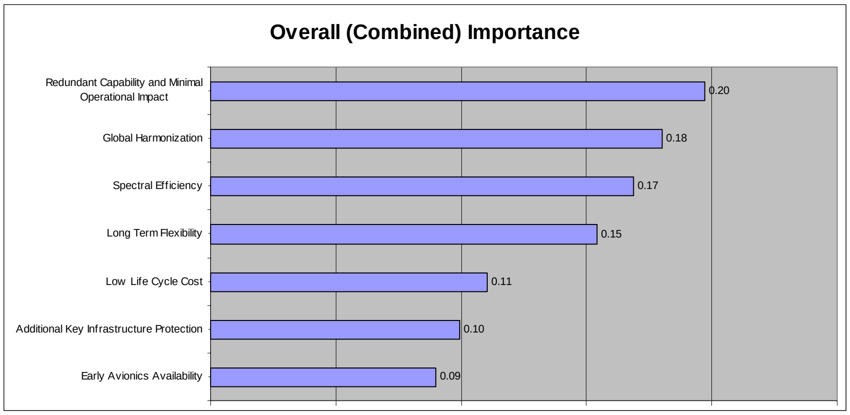

Figure ES-3: Overall (Combined) Decision Factor Weighting

The next step was to assess how well each candidate backup solution met the evaluation criteria. This scoring process, which assigned a value of 0 to 1 to each candidate solution for each criteria, was performed by the assessment team. These results were then combined with the stakeholder weights for the evaluation criteria to identify overall candidate scores and backup solution preferences for each set of stakeholders. A summary of results is provided in Table ES-5. This table identifies the evaluation criteria (e.g. decision factors); stakeholder weights for the evaluation criteria; backup solution scores for each evaluation criteria; and overall scores (combining weights and scores) in the bottom rows of the table.

Table ES-5: Assessment Results – Solution Preference for Key Stakeholder (Sets)

Evaluation Criteria/Decision Factors	**Stakeholder Weighting**				**Evaluator Scoring**		
	All AC	**All GA**	**All Gov/Stnds**	**All**	**D/D/I**	**GNSS/INS**	**eLORAN**
Life Cycle Costs	.16	.07	.097	.11	.4	.8	.7
Redundant & Seamless Failover	.18	.24	.195	.197	0.55	0.5525	0.85
Long Term Flexibility	.16	.18	.13	.14	0.775	0.55	0.85
Avionics Availability	.08	.13	.08	.09	0.925	0.8	0.525
Global Harmonization	.22	.12	.16	.17	0.875	0.65	0.1025
Spectrum Efficiency	.12	.15	.21	.18	0.55	0.9	0.9125
Key Infrastructure Protection	.09	.11	.13	.12	0.255	0.14	0.875
Weighted Score – All AC					.645	.641	.638
Weighted Score – All GA					.643	.636	.709
Weighted Score – All Gov/Stnds					.629	.634	.699
Weighted Score – Overall					.641	.637	.682

Another view of the results is provided in Figure ES-4 (note that the figure below includes the full set of stakeholders considered and associated preferences). The data indicates that for some stakeholders, the eLORAN solution is slightly preferable to the other candidate solutions, and there was very little distinction between the preference of GNSS/INS and DME/DME/INS solutions. Overall, the candidate performance was very close.

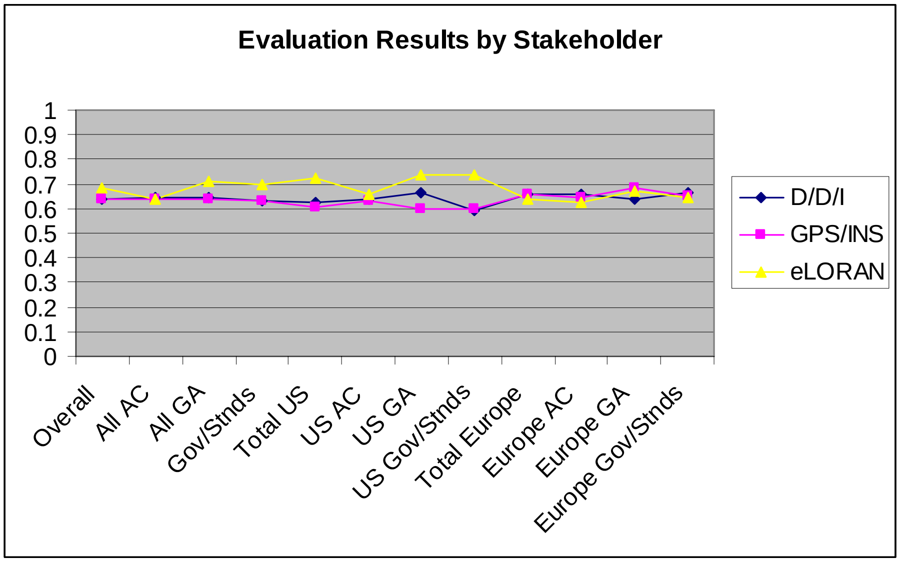

Figure ES-4: Assessment Results – Solution Preference (Key Stakeholder Sets)

Sensitivity assessment of the result above to two evaluation factors, cost and key infrastructure protection, was also investigated (by discounting these factors). The results indicated that there was some sensitivity in the results to the stakeholder set considered as well as to specific decision factors. Based on the stakeholder group considered and set of evaluation factors considered, different SatNav backup solutions were identified as having the highest preference. Overall, there was a slight preference to the eLORAN solution for General Aviation. For commercial aviation, DME/DME/INS and GNSS/INS had a slightly higher preference to eLORAN. When cost was discounted, the preference leaned in favor of DME/DME/INS; when key infrastructure protection was discounted, the preference leaned towards GNSS/INS. Based on the importance of evaluation criteria/decision factors from the government and standardization bodies perspective (developed through the stakeholder survey process), the eLORAN solution was marginally preferable over the other two solutions. When discounting cost, no impact to preference was identified; however when discounting the key infrastructure protection decision factor, preference shifted in favor of GNSS/INS for this stakeholder.

Results Summary

Overall, the final evaluation scores specific to the assessed solutions indicated that there was not one SatNav backup solution that was significantly more preferable to all others for all stakeholders. eLORAN had the highest preference rating overall and for the US aviation segments groups combined, performing more strongly for the General Aviation segment; but preference was only slightly above the other two candidates. In contrast, eLORAN scored third for some aviation segments, specifically some within the European categories.

The DME/DME/INS and GNSS/INS solutions preference were only marginally different among many of the stakeholders, with preference of these solutions passing eLORAN when the Key Infrastructure Protection evaluation factor was discounted (GNSS/INS then had overall highest preference).

Additionally, these solutions had higher preference over eLORAN for the commercial jet aviation segment.

Specific SatNav backup results/recommendations for the benchmark operational NextGen timeframes are provided in Table ES-6 below.

Table ES-6: SatNav Backup Results/Recommendations

	2015	2020	2025
Viable SatNav Backup Options	• DME/DME/INS	• DME/DME/INS • eLORAN • GNSS/INS	• DME/DME/INS • eLORAN • GNSS/INS
Recommendations for SatNav Backup	• DME/DME/INS	• DME/DME/INS • eLORAN • GNSS/INS	• eLORAN • GNSS/INS
Supporting Strategy	• Support DME/DME/INS as a backup solution (assume existing avionics and minimal build-out of DMEs • Continue support for eLORAN ground infrastructure upgrades • Continue support development of eLORAN avionics • Continue support development of smaller/lighter INS avionics	• Support transitioning a combined GNSS/INS and eLORAN solution (GNSS/INS as primary backup solution for Air Carrier complemented with eLORAN as primary backup solution for GA)	• Support GNSS/INS and eLORAN as SatNav backup solutions

The recommendations defined in the table above are reflective of the outputs of the overall AHP assessment methodology that included the following to arrive at scoring results that reflect stakeholder preference:

- Data gathered through stakeholder interviews
- A backup solution screening process that included the application of technical requirements as threshold requirements
- A life cycle cost comparison of solutions
- Stakeholder weighting of other evaluation criteria / decision factors
- An assessment of solutions against the evaluation criteria

The information in the table above indicates that in the 2025 timeframe, the recommendation is for support of eLORAN and GNSS/INS as capable and complimentary SatNav backup solutions. eLORAN scored the highest overall preference rating in the analysis, particularly so in the U.S. and for the General

Aviation stakeholder segment. eLORAN integration into GNSS/eLORAN FMS aviation systems for general aviation and certain air carrier segments could be a viable and capable solution.

This study also recognizes the uncertainties for expanding the eLORAN concept internationally and for achieving global harmonization for this solution. The need for a backup solution outside of eLORAN coverage (including oceanic) necessitates an alternate and suitable backup for many air carriers. Based on the combined scores from all segments, and particularly for the Air Carrier segment, this study recommends GNSS/INS as the complementary backup solution. Note that although this candidate scores nearly identically to DME/DME/INS when considering all decision factors, its preference increased significantly when discounting the decision factor that addresses the desirability to protect key infrastructure.

It is expected that GNSS/INS systems would benefit from the additional blending of eLORAN positioning information where available. It could assist with the early identification of certain satellite signal anomalies. The GNSS/eLORAN/INS integration also addresses the concern for a SatNav backup that could sustain operations in a widespread outage beyond the coast distance of an INS

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REVISION HISTORY

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Table RH-1: Document Revision History

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TR07001	July 6, 2007	Initial Release of Final Report to NGATS Institute
TR07001-Rev 1	July 19, 2007	Removed reference to document restrictions
TR07001-Rev 2	Sept 19, 2007	General edits; Final Report to NGATS Institute

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1. INTRODUCTION

1.1 BACKGROUND

1.1.1 NextGen Satellite Based Navigation

The Joint Planning and Development Office (JPDO) manages a unique public/private partnership to implement a sweeping vision, called the Next Generation Air Transportation System (NextGen), to guide the transformation of the National Air Space (NAS) to meet the needs of the 21st century.

The JPDO identifies key capabilities necessary to transform the NAS. Global Positioning System (GPS) satellite based navigation (SatNav) is an important enabler of the NextGen vision. Modernization plans and augmentation strategies for the GPS will make it a more valuable asset to aviation. The addition of Galileo and possibly GLONASS and COMPASS will further enhance the performance capabilities of SatNav systems.

1.1.2 Satellite Based Navigation Vulnerabilities and Risks

The 2001 Volpe GPS Vulnerability Assessment warns that GPS is vulnerable "to interference and other disruptions that can have harmful consequences. GPS users must ensure that adequate independent backup systems or procedures can be used when needed."[3] That study included an assessment of aviation vulnerabilities and risks due to GPS outages as shown in Table 1-1. The green-colored boxes in the table indicate that safety and continuity of operations can be maintained in the presence of outages. A yellow box indicates a safe, but operationally inefficient level of operation. A red box indicates potentially hazardous or unsafe operations that might result from GPS outages.

Table 1-1: Volpe Study Aviation Vulnerability and Risk Summary [4] [5]

Mode	Application	Impact of GPS Disruption		
		Momentary	Serious	Severe
Aviation	Oceanic Navigation	Minimal	Operational	Operational
	En Route Navigation	Minimal	Operational[1]	Operational[1]
	Terminal Navigation	Minimal	Operational[1]	Operational[1]
	Non Precision Approaches	Operational[2]	Safety[3]	Safety[3]
	Precision Approaches	Operational[2]	Safety[3]	Safety[3]
	ADS Surveillance	Minimal	Minimal[4]	Operational
	Airport Surface Operations	Minimal	Minimal	Operational
	Timing (Communications)	Minimal	Operational	Operational
Momentary Outage: a single, very short term, limited breadth GPS outage (on the order of seconds or a				

[3] DOT Volpe Report: *Vulnerability Assessment of the Transportation Infrastructure Relying on the Global Positioning System*, Final Report, John A. Volpe National Transportation Systems Center, August 29, 2001.
[4] *Ibid*. Table is extracted from Table 5-1, p. 48; outage definitions have been added to the table and are from p. 41 of the study.
[5] The Volpe Vulnerability Study was completed before 9/11. For 'severe outages', it appears that Volpe focused on the safety impact (getting aircraft on the ground) and did not have a full appreciation for the economic impact of ceasing or significantly reducing operations. After the events following 9/11, Volpe better understood how important being able to maintain operations is to the economy.

minute, over a confined region)
Serious Outage: a single, moderate length, limited breadth GPS outage (on the order of minutes or hours, over a confined region)
Severe Outage: a long term, wide breadth GPS outage (on the order of days over wide areas or a series of moderate length outages over a wide area).

[1] This assumes that … controllers can safely respond to Serious and Severe GPS outages.
[2] This assumes missed approach course guidance is not required. If course guidance is required, the disruption could have a safety impact.
[3] This safety risk occurs not because the operations are inherently dangerous without GPS, but rather because possible circumstances combined with loss of GPS may result in a safety or large economic or environmental risk.
[4] This assessment is only for areas covered by SSR [Secondary Surveillance Radar]. For areas not covered by SSR, the impact would be Operational for Serious outages.

In recognition of increased risks to the GPS and other U.S. infrastructure in recent years, the December 17, 2003 *Homeland Security Presidential Directive/HSPD-7*[6]: established "a national policy for Federal Departments and agencies to identify and prioritize United States critical infrastructure and key resources and to protect them from terrorist attacks." A subsequent national policy directs the Secretary of Transportation, in coordination with the Secretary of Homeland Defense, to:[7]

> Develop, acquire, operate, and maintain backup position, navigation, and timing capabilities that can support critical transportation, homeland security, and other critical civil and infrastructure applications within the United states, in the event of a disruption of the Global Positioning System or other space based positioning, navigation, and timing services,..

The importance of SatNav to the JPDO vision; its recognized vulnerabilities and associated risks; and the executive directives and polices produced in response to these vulnerabilities/risks are the motivation for this SatNav Backup Study.

1.2 STUDY OBJECTIVE AND SCOPE

The principal objective of the SatNav Backup Study was to develop a set of potential "backup" Area Navigation (RNAV) solutions for NextGen over a period of time to include 2015, 2020, and 2025. RNAV is defined by ICAO as a: "method of navigation which permits aircraft operation on any desired flight path within the coverage of station-referenced navigation aids or within the limits of the capability of self-contained navigation aids, or a combination of these."[8] For this study, we primarily considered Area Navigation SatNav backup solutions for the following phases of flight:

- En Route
- Terminal

[6] *December 17, 2003 Homeland Security Presidential Directive/HSPD-7*, http://www.whitehouse.gov/news/releases/2003/12/20031217-5.html
[7] U.S Space-Based Positioning, Navigation, and Timing Policy, December 15, 2004
[8] *Performance Based Navigation Manual*, Volume 1, Concept and Implementation Guidance, Working Draft 5.1 – FINAL, 7th March, 2007, p. xix.

- Non-precision Approach (NPA)

SatNav backup candidates for precision approaches and surface navigation are evaluated at a higher level and are discussed in an appendix.

This study consisted of the six subtasks depicted in Figure 1-1. The methodology for performing these subtasks is discussed in detail in Section 2.

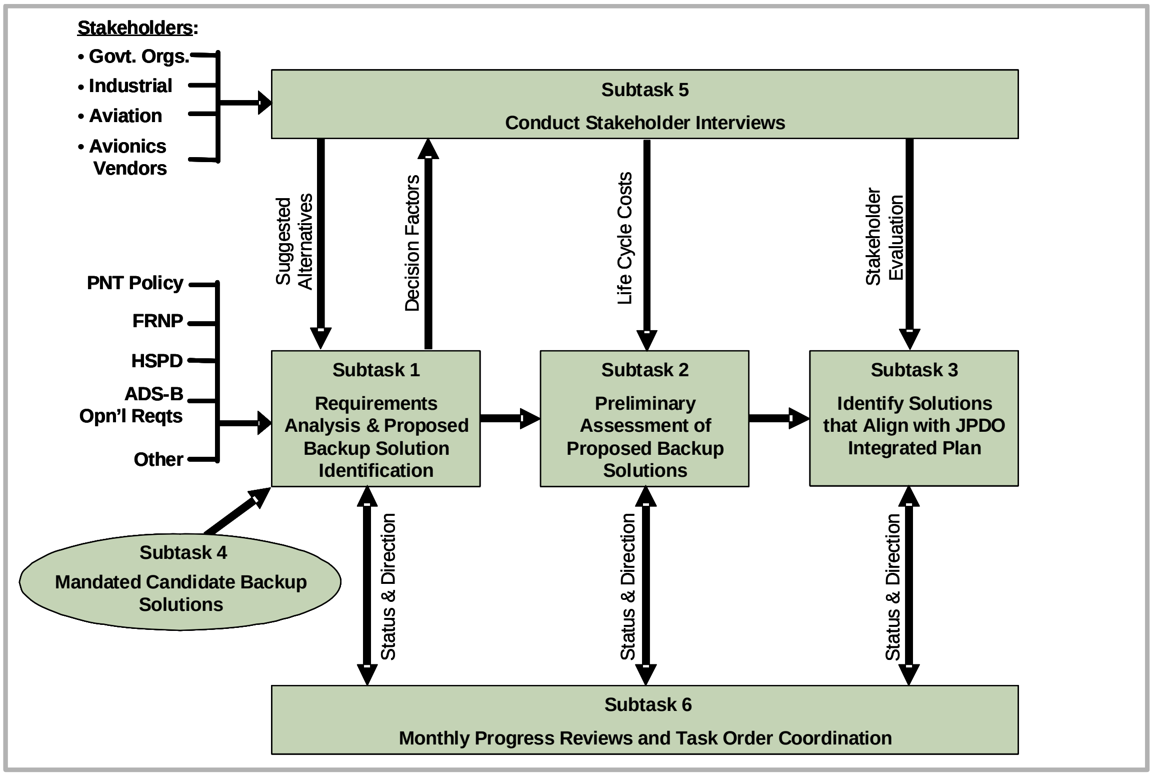

Figure 1-1: Scope of the SatNav Backup Study

1.3 SATELLITE NAVIGATION BACKUP STUDY TEAM

ITT-Advanced Engineering & Sciences was joined by partners QinetiQ and Ohio University Avionics Engineering Center in performing this task.

1.4 REPORT ORGANIZATION

Following this introductory section, this report is organized as follows:

- Section 2: Study Methodology
- Section 3: Requirements Assessment and Evaluation Criteria Definition
- Section 4: Backup Alternatives Definition and Initial Screening
- Section 5: Cost Considerations
- Section 6: Backup Solution Evaluation & Recommendation Development

- Section 7: Summary of Results and Recommendations
- Appendix A: Bibliography
- Appendix B: SatNav Backup of Airport Surface Operations
- Appendix C: SatNav Backup For Precision Approach
- Appendix D: Round 1 Stakeholder Interview Letter & Questionnaire
- Appendix E: Round 2 Stakeholder Interview Questionnaire
- Appendix F: List of Acronyms & Abbreviations

2. STUDY METHODOLOGY

2.1 METHODOLOGY OVERVIEW

Within the aeronautical environment, decision making can be challenging. Many complexities arise from the large number of stakeholders involved, each with differing needs and desires. Additionally, there are often many and sometimes conflicting factors that influence stakeholder decisions with regard to aeronautical systems. The core approach for identification and evaluation of SatNav backup solutions for this study was based on a standardized evaluation methodology, the Analytical Hierarchy Process (AHP), often employed for decision making within the Six-Sigma business improvement process. This methodology is process-oriented, accommodates multi-criteria decisions, and employs customer-focused views and perspectives.

Like all decision making methodologies, the AHP has both strengths and weaknesses. It can accommodate many aspects of a decision organized into a decision hierarchy; support group decision making; apply a clear and comprehensive structure to the decision making process; and provide a means of assessing relative importance of decision factors. With these benefits come some limitations. Specifically, there is an implied assumption that identified decision factors are independent, which is not always the case. Additionally, the process can be time intensive to implement. In spite of these drawbacks, the Analytical Hierarchy Process was found to be highly appropriate for this investigation. Its comprehensive structure and direct use of stakeholder inputs provided a means to foster buy-in of the evaluation process and results.

The standardized Analytical Hierarchy Process is composed of nine task steps, as shown in Table 2-1. The first three steps (1 - 3) of this process consist of defining candidates to consider and applying a screening process to identify those candidates that are most applicable to a defined objective. The next two steps (4 – 5) consist of defining and organizing the evaluation criteria to apply in the assessment. Steps 6 and 7 can be performed in parallel, where Step 6 is a relative comparison of alternative solutions and Step 7 is a relative comparison of evaluation criteria (to establish importance weighting). Finally, Steps 8 and 9 include defining the overall priority of candidate solutions and performing sensitivity analysis.

The process shown in the table has been adapted to the evaluation of candidate SatNav backup solutions. In this adapted approach, several of the process steps have been combined while maintaining the overall approach strategy. The numbered steps identified by the blue boxes in Figure 2-1 closely align with the AHP process steps defined in Table 2-1 (although applied in a slightly different order and in some cases, combining more than one AHP process step).

Table 2-1: Standard Analytical Hierarchy Process Steps

	Name	Description
1	List Alternatives	First step in AHP; identify and list all alternatives
2	Define Threshold Levels	Define minimum requirements that an alternative has to fulfill
3	Determine Acceptable Alternatives	Review all alternatives with respect to threshold levels; alternatives that do not meet these requirements are dismissed
4	Define Criteria	Criteria used to judge the alternatives are defined; several techniques are possible (e.g. pro/con analysis, critical success factor technique, etc)
5	Develop Decision Hierarchy	A hierarchy that identifies the decision goal, and provides an organization of analysis criteria
6	Comparison of Alternatives Pairwise	For each criterion, stakeholders evaluate all candidate solution alternatives pairwise (every possible combination of alternatives is judged with respect to each criterion); this results in a relative ranking of each alternative
7	Comparison of Criteria Pairwise	Stakeholders perform a pairwise comparison of all evaluation criteria; this results in the relative importance of each criterion
8	Calculate Overall Priorities for Alternatives	A linear additive function is used to calculate the overall ranking of an alternative (the relative rankings of an alternative are multiplied by the importance of the corresponding criteria and summed over all criteria)
9	Sensitivity Analysis	"What-if" analysis is used to identify the sensitivity of results to changes in rankings of alternatives and criteria

2.2 APPROACH FOR CANDIDATE EVALUATION

The methodology and workflow employed for this study is shown in Figure 2-1. As shown in figure, the workflow was organized into three major sequential activities: *Requirements Assessment and Evaluation Criteria Definition*; *Backup Alternatives Definition and Initial Screening*; and *Backup Solution Evaluation and Recommendation Development*. These are described as follows.

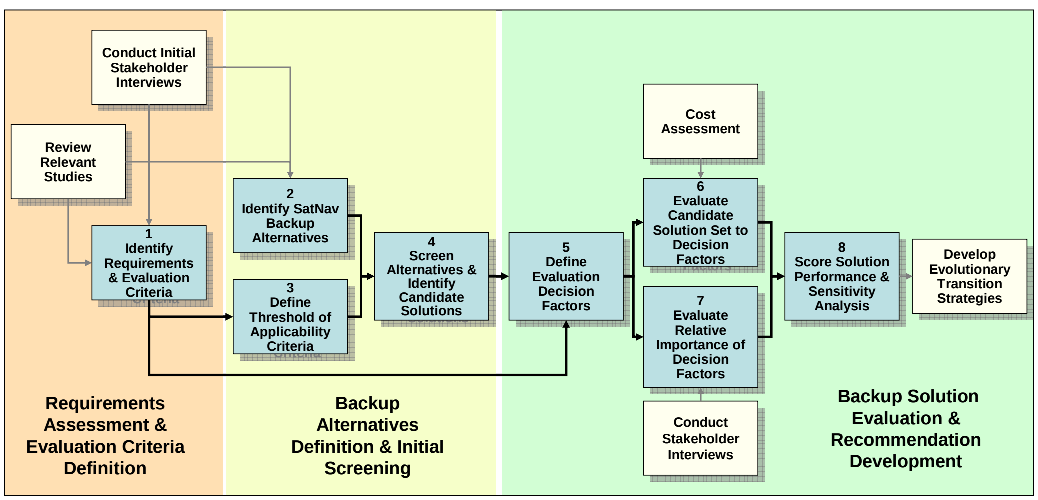

Figure 2-1: SatNav Study Methodology

The *Requirements Assessment & Evaluation Criteria Definition* activity identified applicable requirements for SatNav backup solution evaluation based on review of published navigation performance requirements documents; NGATS operating concepts; Government policies; and studies that address current and future navigation system plans, constraints, and needs. In addition, navigation system stakeholders, including ground system service providers and users, were interviewed to identify their

input on applicable evaluation criteria for consideration of backup solutions. Based on the derived requirements and stakeholder inputs, a set of evaluation criteria for this study were defined.

The *Backup Alternatives Definition and Initial Screening* activity consisted of three steps. The first step was the identification of a preliminary set of alternative candidates for providing SatNav backup capabilities based on review of current navigation capabilities; proposed/planned navigation systems and operating concepts; relevant technical studies; and stakeholder interview results. A concurrent step was the selection of critical threshold criteria to allow an initial screening of the preliminary candidates. Finally, the threshold criteria were used to screen the preliminary candidates and select a smaller set of the most suitable candidates for further consideration.

The final major activity was *Backup Solution Evaluation and Recommendation Development*. In this step, candidate solutions were evaluated against the remaining criteria (those not applied in the screening process); stakeholders were again surveyed to solicit their views/perspectives on the relative importance of the evaluation criteria; and backup solutions priorities/scoring results were computed by combining the candidate evaluations with the criteria weighting information. This information and other relevant candidate solution considerations identified during the course of the study were used to develop SatNav backup solution recommendations.

This report addresses the work performed and associated results corresponding to the work flow defined above.

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3. REQUIREMENTS ASSESSMENT AND EVALUATION CRITERIA DEFINITION

3.1 Requirements Assessment and Evaluation Criteria Process

This section presents an overview of the process used to derive the requirements and evaluation criteria for assessing SatNav backup systems. Figure 3-1 provides a high level view of this activity.

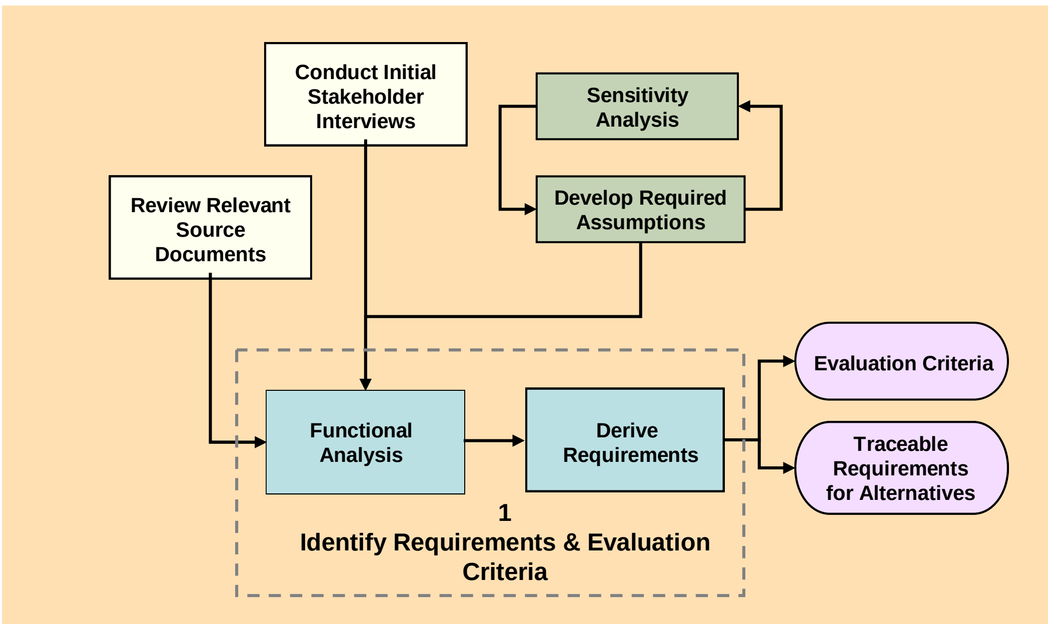

Figure 3-1: Requirements Assessment and Evaluation Criteria Definition

As shown in the figure, requirements were derived as a result of a functional analysis. Because aeronautical navigation systems are already in existence and for the most part, well defined, the essence of the functional analysis for this study was a “middle-out” approach. This consisted of a combination of a top down identification and analysis of fundamental current and future aeronautical navigation system and stakeholder needs and capabilities with a bottom up identification and assessment of existing and planned aeronautical navigation system capabilities and characteristics. Required navigation system functions and evaluation criteria were derived from these identified required needs and capabilities. SatNav backup system performance requirements associated with required aeronautical navigation functions were mainly derived from existing ICAO and RTCA aeronautical standards.

As shown in Figure 3-1, the preliminary focus of the *Requirements Assessment and Evaluation Criteria Definition* activity was the review of relevant source documents to serve as an input to the functional analysis. This review activity is illustrated in Figure 3-2. In addition to the identification of relevant capabilities and the definition of stakeholder and system needs, an important component of this activity

was the determination of the future operational environment for navigation systems, and its associated impact on needs and capabilities. The results of the activities depicted in Figure 3-2 are described in the following sections.

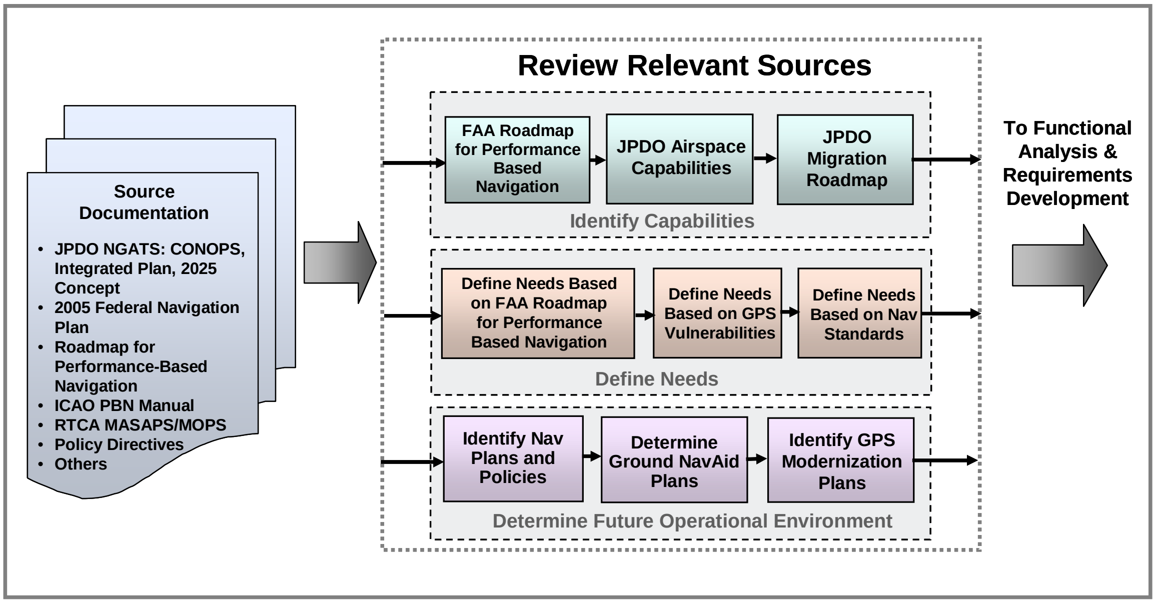

Figure 3-2: Processes in Reviewing Relevant Source Documentation

3.2 FUTURE NAVIGATION OPERATIONAL ENVIRONMENT

3.2.1 The NextGen Future Operational Environment for Navigation

The *Next Generation Air Transportation System Integrated Plan*[9] forecasts significant growth in aircraft operation of up to three times (3X) year 2004 levels by the year 2025. It calls for transformation that brings more flexibility, increased efficiency, and greater safety while meeting the needs of increased capacity. Plans and goals for future navigation system transformation identified in the *NGATS Plan* include the following [italics added]:

- Global harmonization:
  - “Harmonized civil and military equipment as well as operations that require communications, *navigation*, and spectrum availability will be vital in planning and executing global missions.”
  - Transformation direction to “Implement the ICAO Communication, *Navigation*, and Surveillance Air Traffic Management (CNS/ATM) global plan”
- Spectral efficiency: Transformation direction to “create global interoperable communications, *navigation*, and surveillance infrastructure that can function reliably within available spectrum”
- Agile Air Traffic System: “Research is needed to

[9] *Next Generation Air Transportation System Integrated Plan*, United States Department of Transportation, December 12, 2004.

- "Determine the requirements for communications, *navigation*, and surveillance infrastructure to meet the traffic and performance needs of the future in a cost effective manner while accommodating all air traffic, defense, and security stakeholders."
- "Define and evaluate fundamental communications, *navigation*, and surveillance architecture options"

The JPDO *Concept of Operations for the Next Generation Air Transportation System*[10] presents an integrated view of NextGen operations into the 2025 timeframe, including key transformations from today's operations. It describes a future environment that includes the following concepts and capabilities related to navigation[11]:

- Positioning, Navigation, and Timing (PNT) services [that] reduce dependence on costly ground-based navigation aids (NAVAID) by providing users with current location and any corrections, such as course, orientation, and speed, that are necessary to achieve the desired destination.
- PNT Services [that] are provided where and when needed, in accordance with demand and safety considerations, to enable reliable aircraft operations in nearly all conditions. Instead of being driven by geographic constraints, PNT Services allow operators to define the desired flight path based on their own objectives.
- Equivalent Visual Operations: For aircraft, this capability, in combination with positioning, navigation, and timing, enables increased accessibility, both on the airport surface and during arrival and departure operations.
- Trajectory-Based Operations: Transformation from (2006): Required navigation performance (RNP) operations … used initially to manage complexity and increase capacity, to (2025): flights are managed through use of four-dimension trajectories (4DT) that specify accurate current and future aircraft position
- Low-Visibility Approach and Departure Procedures: Aircraft with appropriate cockpit displays and automation support conduct landings and takeoffs safely in low-visibility conditions without relying on ground-based infrastructure by using onboard navigation, sensing, and display capabilities.
- With the deployment of new precision approaches to most airfields, as enabled by satellite navigation technologies and RNP, access to most non-major airports will become safer and more reliable.
- NAVAIDs: The transition to satellite-based IAPs [Instrument Approach Procedures] will free up airport surface movement areas previously constrained because of ground-based navigation systems
- The primary system providing PNT Services is expected to be some form of global navigation satellite system (GNSS), perhaps with a satellite-based augmentation system (SBAS), providing increased accuracy, availability, and integrity to users of the service.

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[10] *Concept of Operations for the Next Generation Air Transportation System, Joint Planning and Development Office*, Version 2.0, 13 June 2007.

[11] Ibid. The bulletized excerpts are from the following pages: ES-2, 1-5, 1-5, 2-6, 2-23, 3-16, 3-25, 5-9, and 5-10 respectively.

Ground-based augmentation may also be used in high-density terminal airspace. Backup systems are critical to the PNT system and are required.

- With PNT Services, a user (or COI)–determined integrated air picture supports SSA [Shared Situational Awareness] to all users of the NextGen.

The *2005 Progress Report to the Next Generation Air Transportation System Integrated Plan*[12] predicts: "SATNAV will become the primary means of navigation in domestic air space." It describes the following future operational concepts for navigation[13]:

- [Performance Based Navigation][14] will provide navigation services where and when they are needed, enabling safe and reliable aircraft operations in all but the worst weather conditions.
  - This capability will likely include a next generation of Global Positioning System (GPS) satellites with non-terrestrial navigation augmentation for operations in weather conditions equivalent to today's Category I approaches, as well as hybrid global navigation satellite system (GNSS)/inertial avionics for operations in weather conditions equivalent to today's Category II/III approaches.
  - Elimination of multiple legacy systems will reduce the air transportation system costs as well as user costs associated with maintaining proficiency over multiple navigation systems.
- Equivalent-Visual Operations: Through sensors and satellites, the system will allow for precise navigation and other critical information to be sent directly into the cockpit… …this capability will become operational in about 10 years…
- Satellite navigation (SatNav) is also a key enabling technology to reduce separation standards and expand airspace capacity while enhancing safety. Once in place, SatNav will become the primary means of navigation in domestic airspace in segment 2 [FY10 – FY13]. These steps will significantly increase airspace capacity and efficiency, allowing the FAA to gradually retire its inventory of ground-based navigation aids in later segments of the 2025 portfolio.
- RNP routes are expected to be a more efficient alternative to today's procedures.

The *2005 Progress Report* provides the timeline shown in Figure 3-3 for the transition of future navigation operational capabilities.

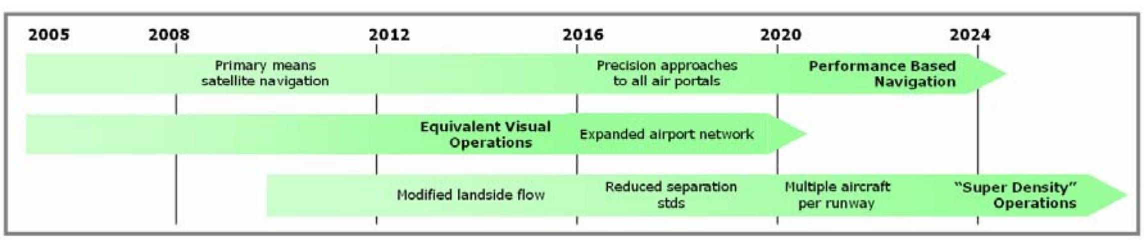

Figure 3-3: NextGen Timeline for Future Navigation Concept Transition[15]

[12] *2005 Progress Report To The Next Generation Air Transportation System Integrated Plan*, Joint Planning and Development Office, 2005.
[13] Ibid. The bulletized excerpts are from the following pages: 8-9, 9, 13, and 13 respectively.
[14] JPDO now uses the term 'Performance Based Navigation', replacing 'Broad Area Precision Navigation'.
[15] Ibid. p. 11.

3.2.2 U.S. Radionavigation Plans Related to Future Navigation Operations

The (2005) Federal Radionavigation Plan (FRP) is the official source of radionavigation policy and planning for the Federal Government. The Federal Government operates radionavigation systems as one of the necessary elements to enable safe transportation and encourage commerce within the United States. Its goal is to provide radionavigation services in the most cost effective manner possible.

The FRP includes the operation and modernization of GPS and the WAAS augmentation system. As GPS services with augmentations are implemented, the demand for services provided by other radionavigation systems is expected to decrease. It is the policy of the U.S. Government not to rely on a single system for positioning, navigation, and timing and the United States will provide redundant radionavigation service where required. Potential backups to GPS for navigation applications include other radionavigation systems, operational procedures, and a combination of systems and procedures. In addition to GPS and its augmentation systems, the Federal radionavigation systems include Long Range Navigation (LORAN), VHF Omni directional Range (VOR), Distance Measuring Equipment (DME), Tactical Air Navigation (TACAN), Instrument Landing System (ILS), Microwave Landing System (MLS), aeronautical nondirectional beacons (NDB), and marker beacons. A summary of these systems is given in Table 3-1.

Table 3-1: 2005 FRP: Aviation Radionavigation Systems (Not Including GPS)

Radionavigation System	Operator	Number operated
VOR	FAA	60
	DoD	15
VOR/DME	FAA	405
	DoD	18
VORTAC (DME portion used by civil aviation)	FAA	590
	DoD	24
DME collocated with NDBs	FAA	30
ILS	FAA	1,275 • 225 are localizer only • 115 are CAT II and III
	DoD	160
MLS	FAA	Few, phase out anticipated
Aeronautical Nondirectional Beacons (NDB)	FAA	225
	DoD	50
	Non-Federal	1075
Marker Beacons	FAA	phase out anticipated
LORAN-C (being upgraded to eLORAN)	US Coast Guard	Coverage US and Canada

The FRP notes that the FAA is planning to transition into providing Satellite based navigation (SatNav) services based primarily GPS with augmentation by WAAS, with CAT II / III precision approach service

based on LAAS and ILS. With this transition plan, the role and the number of ground based navigational aids will diminish. Milestone goals in this transition strategy are summarized in Table 3-2.

Table 3-2: 2005 Federal Radionavigation Operating Plans

2015	2020	2025
• NDB only in remote areas and international gateways • Some VORs decommissioned, others relocated • Low power DMEs added to support ILS precision approaches • TACAN maintained until GPS based procedures are in place • ILS maintained • MLS decommissioned • LORAN-C / eLORAN (pending policy decision)	• 50% reduction in VORs and CAT I ILS aids • DMEs provide redundant capability for en route and terminal operations • ILS provides precision approach service at major terminals • eLORAN (pending policy decision)	• Dependent on achieved satellite navigation program milestones • Ground aids have limited roles as backup for Satellite Navigation and for Minimum Operational Network for non-SatNav users • ILS-Cat II / III likely maintained • eLORAN (pending policy decision)

It is an assumption of this study that GNSS will be the primary navigational aid in aviation use by 2015. The FRP indicates that maintaining and possible expansion of ground based DME to support en route and terminal navigation is an important strategy through 2020. Also important is the retention of a sufficient number of ILS systems to enable precision approach capability at major airports.

3.2.3 GNSS Modernization Plans for Future Navigational Operations

As of March 2007, the GPS constellation had 30[16] [17] actively transmitting satellites. The baseline operational level is 24 satellites. Modernization strategies for the space and control segments continue to be secure and increase the value for both military and civil applications.

The first satellite of Block II R-M was launched September 2005 and there are now three operational satellites in this class. The benefit to civil users is the addition of a new civil frequency L2C. A GPS receiver using multiple GPS frequencies would be capable of performing corrections for ionospheric related errors, and thus achieve higher accuracy. Additional frequencies also reduce the threat to the loss of GPS from unintentional interference sources.[18]

[16] GPS information and future timeline in this section draws heavily from *GPS Status and Modernization*, briefing to the National PNT Advisory Board, 29 March 2007, Col. Allan Ballenger.
[17] Satellite locations and their delivered performance are important metrics for determining SatNav capability.
[18] An unintentional interference source would not likely disrupt more than one GPS signal frequency. However, the loss of one frequency could impact the capability of a navigation receiver to autonomously correct for ionospheric errors.

Of particular value to aviation is the addition in GPS Block II-F of a third civil signal-L5 within the frequency spectrum reserved for aeronautical use. The current estimate for first II-F launch is July 2008. The GPS modernization then follows with GPS IIIA. Full operational capability with L1, L2C, and L5 is expected by 2017.

The Wide Area Augmentation System[19] (WAAS) was developed for civil aviation and improves the accuracy, availability, and integrity of GPS derived position information. WAAS is one of a number of navigation systems that can provide position information that supports RNAV operations. Using the WAAS signal, accuracy is improved from approximately 20 meters to 1.5 – 2 meters in both horizontal and vertical dimensions. WAAS also provides pilot alerting within 6 to 8 seconds when the input signals for positioning are not usable. With this improved performance, a vertically guided approach service known as localizer performance with vertical guidance (LPV) enables pilots to descend (with stabilized vertical guidance) to decision heights as low as 200 feet. A similar European service called European Geostationary Navigation Overlay Service (EGNOS) is expected to be available for aviation in 2008. For Japan, the similar service is called Multi-functional Satellite Augmentation System (MSAS).

A ground based augmentation system (GBAS) for aviation called Local Area Augmentation System (LAAS) is a research and development project focusing on the resolution of integrity issues. It is expected that LAAS will meet the high accuracy, integrity, and availability requirements that will enable service for CAT I, II, and III precision approach operations. This concept is in the prototype and proof of concept state.

The European Galileo project will be a valuable complement to GPS. It will have space and ground control segments similar to GPS. Major policy issues on Galileo design and services are currently being defined. Through cooperation with the US, Galileo is expected to have many features which interoperate with GPS. Similar to GPS, Galileo will also provide multiple signals (E1[20] and E5a/E5b) for aeronautical users to provide improved accuracy and integrity. The primary benefit to SatNav with the addition of Galileo is in higher availability. The challenging goal of Galileo for 30 launches between 2006 and 2010 is viewed as somewhat optimistic by a few years.

The Russian GLObal NAvigation Satellite System (GLONASS) constellation has 11 operating satellites as of early 2007 with a goal of 24 satellites by 2010. The present GLONASS signals are frequency division multiple access (FDMA) as contrasted with GPS and Galileo signals which are code division multiple access (CDMA). The differences between FDMA and CDMA signals add complexity and cost to GPS/GLONASS or GPS/Galileo/GLONASS receivers. Russia is considering the interoperability concerns with a possible policy decision expected by the end of 2007. The needed boost for GPS/GLONASS receiver development is a stable GLONASS constellation.

[19] WAAS is a type of Satellite or Space Based Augmentation System (SBAS)
[20] E designation is 'Europe'. E1 and E5a overlay the GPS L1 and L5 frequency spectrum. E5b spectrum is adjacent to E5a. L1/E1 and L5/E5a/E5b frequencies are within allocated Aeronautical Radio Navigation Services bands.

The Chinese have a regional navigation system, called Beidou, based on three satellites launched into geostationary orbit in 2000 and 2003. On April 14, 2007, China launched into low earth orbit the first satellite of a constellation called Compass that could also provide future global navigational service.

3.2.3.1 Future GNSS Benefits to Air Navigation

The modernization to GPS and the addition of other global constellations will provide significant benefits to avionics. The combined use of L1 and L5 frequency signals will enable receivers to autonomously estimate and provide significant correction for ionospheric effects.

Added satellites will improve the accuracy, coverage, continuity, and integrity. Increased integration of Receiver Autonomous Integrity Monitoring (RAIM) into GPS avionics enables these avionics to determine the consistency of position data, and further to identify and isolate a possibly faulty signal from the calculations to derive position. These improvements may extend the capability of airborne navigation receivers and reduce the need for supporting ground or space based augmentation systems.

3.2.4 Non-U.S. Future Navigation Perspectives

The European navigation strategy goals are summarized by the following points[21]:

- Achieving a total RNAV environment with defined RNP values for all operations ECAC-wide
- Facilitating the implementation of the ‘free routes’ concept
- Supporting the continued operations of aircraft with lower capabilities as long as operationally feasible
- Supporting the continued operations of State aircraft, in line with the principles of the overall ATM 2000+ Strategy
- Implementing 4D RNAV operations, to support the transition to a full gate to gate management of flight by 2015
- Providing positioning and navigation data at the required performance levels to support the various applications in the ATM/CNS environment
- A judicious deployment of the space-based infrastructure and a rationalization of supporting ground-based infrastructure for all phases of flight, ensuring the transition to GNSS, in line with ICAO recommendations.

The development and implementation timeline of this strategy for the various phases of flight operations is presented in Figure 3-4. The transitioning role of the infrastructure navigation aids in support of this strategy is presented in Figure 3-5. Similar to U.S. strategy, VOR networks provide a diminishing role.

[21] *Navigation Strategy for ECAC*, edition 2.1, European Air Traffic Control Harmonisation and Integration Programme, EUROCONTROL.

SESAR (Single European Sky ATM Research) is the organization formulating the European air traffic infrastructure modernization program. Its goals include developing the new generation air traffic management system. The JPDO and SESAR have a Memorandum of Understanding to provide cross linkages in their respective developments.

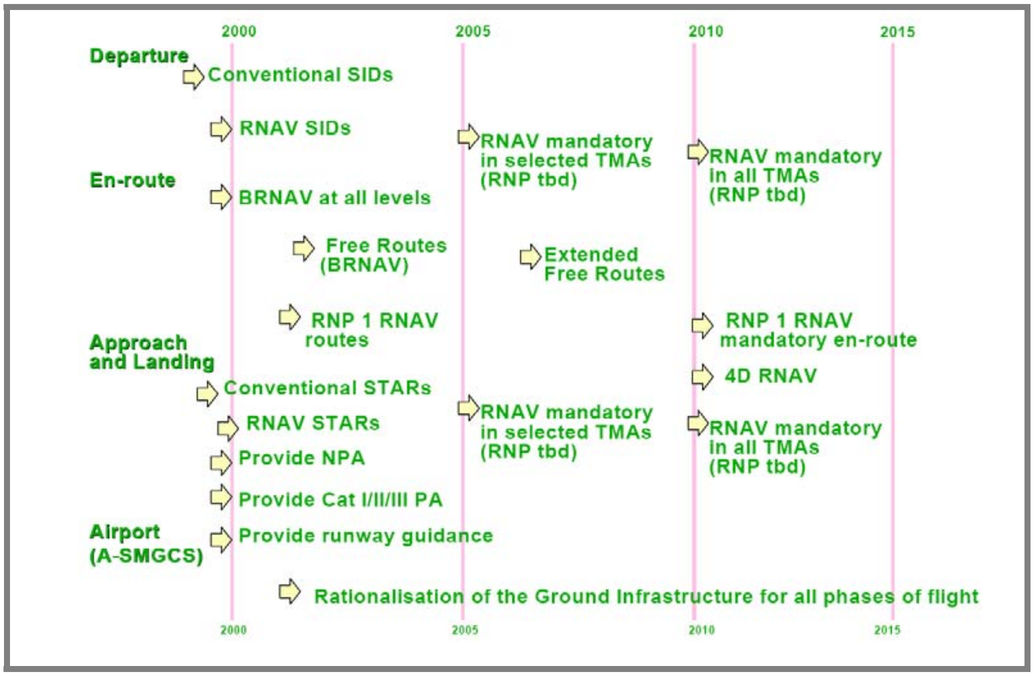

Figure 3-4: European Navigational Strategy for Air Space Operations through 2015

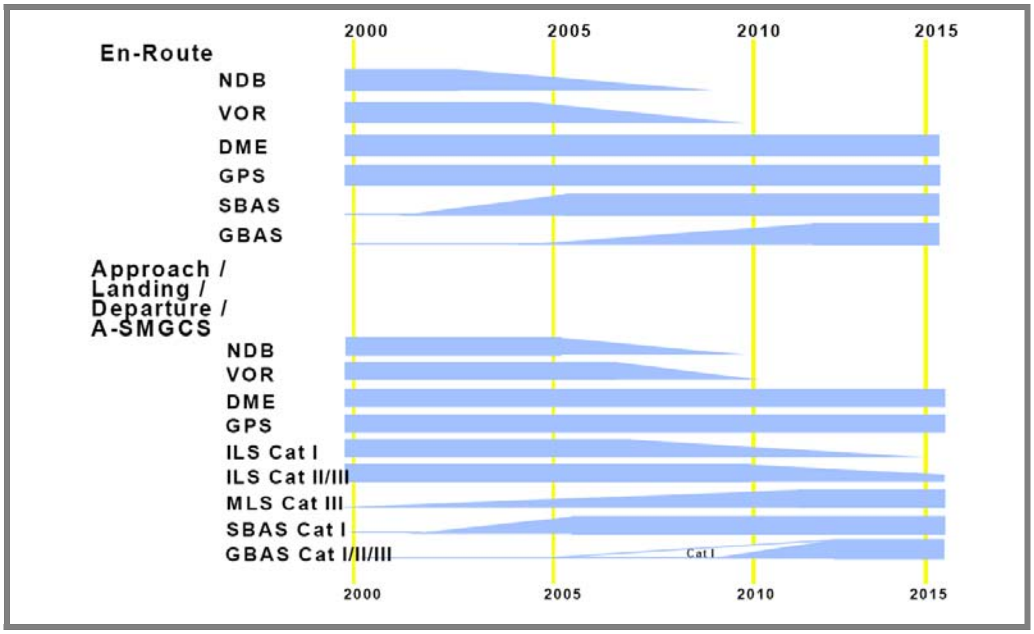

Figure 3-5: European Navigational Infrastructure Strategy through 2015

3.2.5 Summary of Future Navigation Operational Concepts

Table 3-3 summarizes the navigation operational concepts planned for the NextGen future operational environment, and described in the preceding sections.

Table 3-3: Future Navigation Operational Concepts

Future Navigation Operational Concept	Source
Globally harmonized military and civil navigation systems, operations, and plans	Next Generation Air Transportation System Integrated Plan
Spectrally efficient global interoperable navigation infrastructure	Next Generation Air Transportation System Integrated Plan
Navigation architecture for an Agile Air Traffic System	Next Generation Air Transportation System Integrated Plan
Positioning, Navigation, and Timing (PNT) services independent of ground-based NAVAIDs	JPDO Concept of Operations for the Next Generation Air Transportation System
PNT Services provided in accordance with demand and safety	JPDO Concept of Operations for the Next Generation Air Transportation System
Equivalent Visual Operations for aircraft	JPDO Concept of Operations for the Next Generation Air Transportation System, 2005 Progress Report to the Next Generation Air Transportation System Integrated Plan
Transformation from RNP operations to use of 4D trajectories	JPDO Concept of Operations for the Next Generation Air Transportation System
Low-Visibility Approach and Departure Procedures by using onboard navigation, sensing, and display capabilities	JPDO Concept of Operations for the Next Generation Air Transportation System
GNSS with SBAS	JPDO Concept of Operations for the Next Generation Air Transportation System
Performance Based Navigation	2005 Progress Report to the Next Generation Air Transportation System Integrated Plan
DMEs providing redundant capability for en route and terminal operations	2005 Federal Radionavigation Plan
eLORAN (pending policy decision)	2005 Federal Radionavigation Plan
ILS-Cat II / III likely maintained for precision approach service at major terminals	2005 Federal Radionavigation Plan
GNSS with SBAS	Briefing to the National PNT Advisory Board

3.3 FUTURE NAVIGATION NEEDS AND CAPABILITIES

3.3.1 Needs Based on GPS Vulnerabilities and Risks

According to the Volpe GPS Vulnerability Report[22]:

- GPS risks are a function of the probability of intentional and unintentional interference and the transportation-related consequences of loss of the GPS signal. The probability of interference is, in turn, a function of the vulnerabilities of the GPS system to disruption and the threats that could be made against the GPS system.
- GPS is vulnerable to interference that can be reduced but not eliminated. Because of the increasing reliance of transportation upon GPS, the consequences of loss of the GPS signal can be severe (depending upon its application), in terms of safety and environmental and economic damage to the nation, unless the threats are mitigated.

[22] Bulletized excerpts are from *Volpe GPS Vulnerability Assessment Report*, pp. ES-3 through ES-5

- Serious consequences [due to GPS disruptions] are very unlikely to occur, and can be avoided by awareness, planning, and supplementing GPS with a backup system or operational procedures when it is used in critical applications
- The potential for denying GPS service by jamming exists. The potential for inducing a GPS receiver to produce misleading information exists. Loss of GPS satellites or the Operational Control Segment could also impact GPS service, but attacking these elements can be more challenging and likely would produce a more aggressive U.S. Government response than jamming GPS users.
- The GPS service is susceptible to unintentional disruptions from ionospheric effects, blockage from buildings, and interference from narrow and wideband sources. Some natural phenomena such as ionospheric distortions and scintillation can be predicted. These disruptions are most noticeable for users of single-frequency (L1) receivers.
- The GPS signal is subject to degradation and loss through attacks by hostile interests. Potential attacks cover the range from jamming and spoofing of GPS signals to disruption of GPS ground stations and satellites.

Findings and recommendations particularly relevant to this study include the following[23]:

- Backups for positioning and precision timing are necessary for all GPS applications involving the potential for life-threatening situations or major economic or environmental impacts. The backup options involve some combination of: (1) terrestrial or space-based navigation and precision timing systems; (2) on-board vehicle/vessel systems; and (3) operating procedures.
- Conduct a comprehensive analysis of GPS backup navigation and precise timing options including VOR/DME, ILS, LORAN-C, inertial navigation systems, and operating procedures.

The identification and recommendation of Satellite Navigation backup systems to mitigate GPS threats of disruption is a motivation for this study. The implementation of a SatNav backup strategy will provide both mitigation for such disruption and an important deterrent.

3.3.2 NextGen Navigation Capabilities

Section 3.2 describes the NextGen future navigation operational environment. Associated with this future operational environment are the corresponding future PNT service capabilities. Table 3-4 contrasts current PNT capabilities with PNT capabilities in the 2025 timeframe.

3.3.3 Future PNT User Needs

The Position, Navigation, and Timing (PNT) Architecture Development Team[24] is formulating a strategic vision for 2025 to sustain the U.S. preeminence in this area and to meet long-term PNT user needs. This team, under the leadership of the National Space Security Office (NSSO) and the Department of Transportation Research and Innovative Technology Administration (RITA), consists of approximately

[23] Ibid. p.ES-6.
[24] ITT-AES supported the NGATS Institute and the JPDO through participation on the Architecture Development Team.

sixty military, civil government, academic, and industry stakeholder organizations. The objective is to provide effective and efficient PNT capabilities focused on the 2025 timeframe and an evolutionary path for government provided PNT services. The vision will guide decision making on the near and mid term PNT capabilities.

Table 3-4: NextGen PNT Capabilities

Significant Transformation	2006 Current Capability	2025 NextGen Capability
Robust PNT Services	• Air routes are mostly defined by fixed ground-based navigational aids. • Expanding use of RNAV and RNP procedures • Costly ground-based infrastructure in parallel with space-based infrastructure	• Air routes are independent of the location of ground-based navigation aids. • RNAV is used everywhere; RNP is used where required to achieve system objectives, which reduces controller workload and increases efficient use of NAS resources (airspace and runways). • System performance meets operational needs to service the demand. • Increased availability of instrument approach procedures with lower weather minimums at smaller airports • Reduced costs to ANSP to provide better navigation services

User applications of PNT services are quite diverse and growing rapidly. Figure 3-6 illustrates PNT user perspectives by application and by domain, and denotes a large number of civil aviation PNT users.

Through an understanding of the user applications needs, the team has identified performance gaps based on the current (2007) PNT architecture. Several gaps point to the following needs relevant to aviation:

- Need for higher accuracy (with integrity needed)
- Need for higher availability, for example for use In Electromagnetically Impeded Environments
- Need for notification of Degraded/Misleading Info (Integrity)

The PNT Architecture Development Team has focused on the features needed in the 2025 PNT architecture before considering possible programs or upgrades. It is expected that the 2025 vision will provide adequate support for the PNT needs of aviation. The final architecture will provide guidance for decision makers to provide efficient and effective PNT services. It is expected that this study will provide usable input to the PNT Architecture Development Team study to help identify what necessary redundancy is required to support the primary navigation service provided by GPS/GNSS.

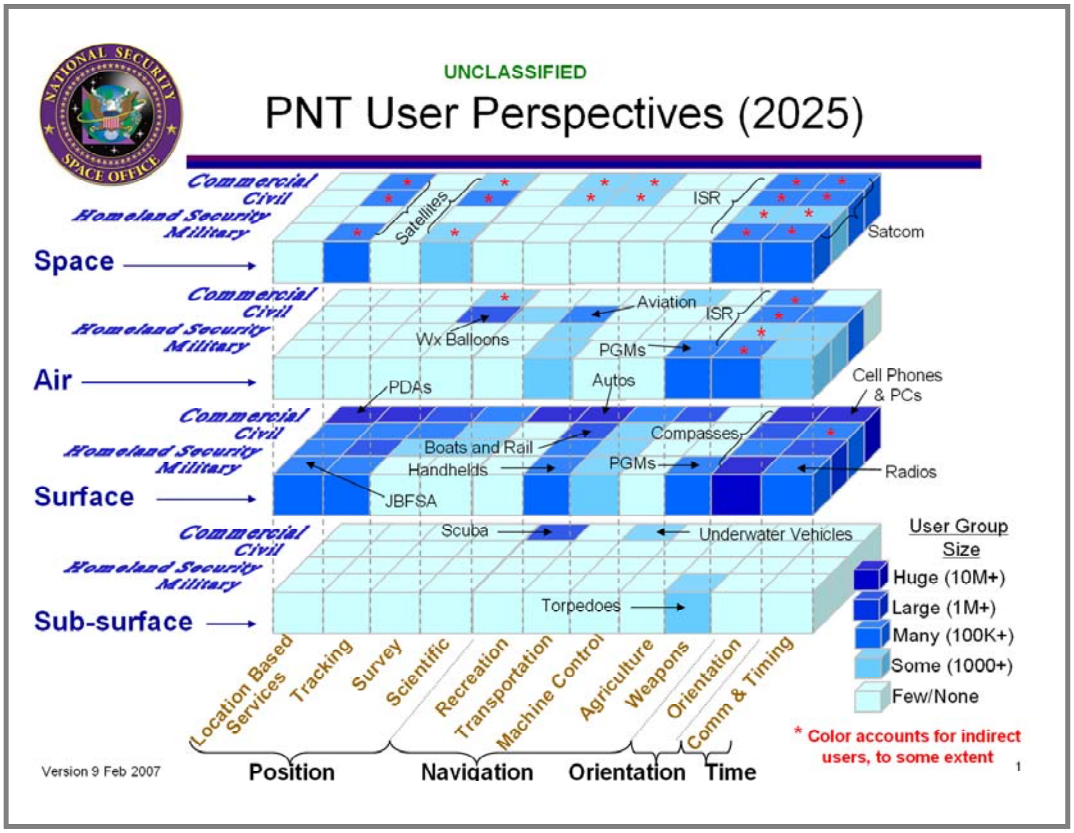

Figure 3-6: PNT User Perspectives

3.3.4 Future Needs Based on the FAA Roadmap for Performance Based Navigation

The FAA's *Roadmap for Performance-Based Navigation*[25] provides a high level strategy for the evolution of navigation capabilities to be implemented in the near term (2006-2010), mid-term (2011-2015), and far term (2016-2025). Performance-based navigation (PBN) is a framework for defining a navigation performance specification along a route, during a procedure, or in airspace within which the aircraft must comply with specified operational performance requirements. RNAV and RNP are the two key elements of PBN in the *Roadmap*.

The expected progress in implementing the *Roadmap's* defined strategies as well as expected navigation performance requirements are shown in Figure 3-7. These performance requirements are a significant contributor to identifying the operational environment and needs of a SatNav backup system.

[25] *Roadmap for Performance-Based Navigation*, Version 2.0, Federal Aviation Administration, July 2006.

Near Term (2006-2010)	Mid Term (2011-2015)	Far Term (2016-2025)
En Route ❐ RNAV Q routes ❐ RNP-2 routes ❐ T routes and lower MEAs ❐ Requirements to incorporate aircraft navigation capabilities into en route automation **Oceanic** ❐ RNP-10 and 50/50 NM lat/long Pacific ❐ RNP-10 and 60 NM lat in WATRS ❐ Expand 30 NM longitudinal/ 30 NM lateral separation (30/30) in the Pacific ❐ Explore RNP-4 in NAT **Terminal** ❐ RNAV SIDs/STARs at OEP airports ❐ RNP-1 SIDs/STARs where beneficial ❐ Automation requirements for merging RNAV arrivals ❐ Concepts for RNAV and RNP with 3D, constant descent arrivals (CDA), and time of arrival control **Approach** ❐ At least 25 RNP SAAAR per year ❐ 300 RNAV (GPS) per year ❐ Standards for closely spaced and converging runway operations based on RNP	**En Route** ❐ RNP-2 routes ❐ T routes and lower MEAs ❐ Enhanced automation incorporating aircraft navigation capabilities ❐ At end of mid term, mandate RNP-2 at and above FL290, and mandate RNAV at and above FL180 **Oceanic** ❐ Limited RNP-4 and 30 NM lat in WATRS ❐ Increase use of operator-preferred routes and dynamic re-routes **Terminal** ❐ RNAV SIDs/STARs at many of the top 100 airports ❐ RNP-1 or lower SIDs/STARs where beneficial ❐ Airspace redesign and procedures for RNAV and RNP with 3D, CDA, and time of arrival control ❐ At the end of mid term, mandate RNAV for arriving/departing at OEP Airports **Approach** ❐ At least 50 RNP per year ❐ 300 RNAV (GPS) per year ❐ Closely spaced parallel and converging runway operations based on RNP ❐ Satellite-based low visibility landing and takeoff procedures (GLS)	**Performance-Based NAS Operations** ❐ RNP Airspace at and above FL290 ❐ Separation assurance through combination of ground and airborne capabilities ❐ Strategic and tactical flow management through system-wide integrated ground and airborne information system ❐ System flexibility and responsiveness through flexible routing and distributed decision-making ❐ Optimized operations through integrated flight planning, automation and surface management capabilities ❐ Mandate RNAV everywhere in CONUS ❐ Mandate RNP in busy en route and terminal airspace

***Figure 3-7: FAA Roadmap for Performance-Based Navigation*[26]**

Within the *Roadmap* framework, RNAV and RNP specifications can be defined to be satisfied by a range of navigation systems. RNAV operations allow aircraft better access and permit flexibility of point to point operations by removing the previous links between navigation and a specific navigation aiding system. RNP operations introduce the requirement for onboard performance monitoring and alerting. RNAV and RNP specifications facilitate more efficient design of airspace and procedures, benefiting users with improved flexibility, and improving the airspace capacity for future growth.

As shown in Figure 3-7, the FAA expects to mandate specific navigation requirements such as RNP-2 at particular points on the roadmap timeline. RNP-2 is example of the navigation requirements terminology *RNP-X*, where the value of *X* refers to the required distance in nautical miles (NM), from the intended horizontal position within which an aircraft must be at least 95 percent of the total flying time. This terminology is discussed in greater detail in Section 3.4.

The *Roadmap for Performance-Based Navigation* seeks to harmonize FAA PBN activities with PBN and RNAV standards development activities within the aeronautical standards organizations, in particular ICAO, Eurocontrol, and RTCA. Section 3.4 describes relevant ICAO and RTCA PBN related standards and specifications.

[26] Ibid. p. 11.

3.3.5 Stakeholder Needs

An essential element of this study was the incorporation of the views, opinions, needs/requirements, and recommendations of the aviation stakeholders relating to the selection of SatNav backup solutions. The study included two rounds of stakeholder interviews (see Figure 3-8). The first round of the interviews solicited stakeholder opinions, needs, candidate suggestions, and cost threshold data with mostly open ended questions as part of the Requirements Assessment and Evaluation Criteria Definition activity of this study. The interview results were analyzed and stakeholder characteristics, needs, and desired features were identified.

The second round interviews were conducted as part of the Backup Solution Evaluation and Recommendation Development activity of this study and provided the input to determine the weighting of the evaluation criteria with a tightly structured questionnaire.

This section presents the results of the first round of interviews - stakeholder inputs to determine stakeholder characteristics, needs, and desired features.

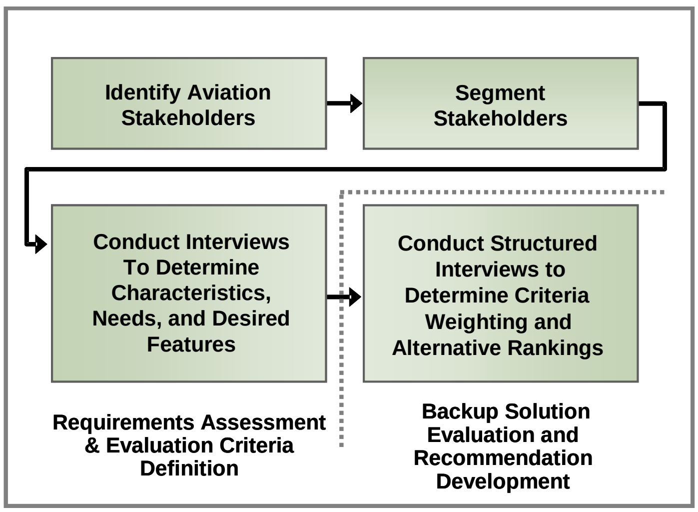

Figure 3-8: Stakeholder Interview Process

3.3.5.1 Aviation Stakeholder Segments

The major segments and sub-segments of the aviation community stakeholders interviewed for this study included the following:

- Air Carrier
  - International
  - Domestic (CONUS, Europe)
  - Regional
  - Freight Carrier
- General Aviation

  - Business including Air Taxi
  - Other
- Military
- Airframe builders
- Avionics manufacturers
- Government/Regulatory/Standards groups

The study team identified credible representatives from these aviation segments in both the United States and Europe.

3.3.5.2 Round 1 Interview Objectives

The objectives of the first round of stakeholder interviews were to:

- Determine the present usage and reliance on satellite based navigation
- Determine the expected usage and reliance on satellite based navigation in 2025
- Determine the operational implications if SatNav was disrupted for a short 3 minute interval
- Determine the operational implications if SatNav was disrupted for a longer 3 day interval
- Determine the cost implications if SatNav was disrupted for a short 3 minute interval
- Determine the cost implications if SatNav was disrupted for a longer 3 day interval
- Solicit an opinion if a SatNav backup system is necessary with the supporting rationale
- Solicit recommendations for candidate SatNav backup system solutions
- Identify important needs and desired features for recommended SatNav backup system solutions.

The first round of interviews was conducted by telephone, primarily with two study team members present on the call. The letter sent in advance of the interview and the questionnaire that provided the interview structure are presented in Appendix D.

3.3.5.3 Round 1 Stakeholder Interview Results – Characterization

A high level characterization of each of the various aviation segments was derived from the interview responses. These are presented in Table 3-5.

Table 3-5: High Level Characterization of Air Carrier Segment

Major Segment Category	Sub Category	Characterization
Air Carrier	International	Values Interoperability and common standards
		Would like common backup for US / Europe
		Long equipage cycles ~ 25 years
		See DME/DME/INS and ILS as backup
	Domestic (CONUS, Europe)	Backup should provide same level of performance as the prime
	Regional	More likely to fly smaller airports than major carriers
		More flights into less equipped terminal areas (lower DME/DME coverage)
		More flights into less equipped airports (without Instrument Landing Systems (ILS))
		Aggressive in using GPS/WAAS as primary
	Freight Carrier	Arrival and departure traffic sequencing clumped
		Cost issue if efficient air sequencing and traffic flow are disrupted
General Aviation	Business including Air Taxi	Likely equipage (DME/ILS/VOR). Some larger ones may have INS.
		Equipage for lower altitudes; may use VOR for traditional route structure.
		Air Taxi will fly RNAV with RNP-0.3 requirements. Very flexible, book seat when you need it to where you want to go.
		Air Taxi values the potential of GPS/WAAS for precision approaches at secondary airports
	Other	Cost sensitive
		May not add satellite navigation backup capability
Military		Large number of ground aids unique to the military- TACAN, DMER
		No policy for civil use of DoD owned TACAN and DME facilities
		Military is large user of national air space
Airframe builders		Enthusiastic about capability of SatNav
		Want international standards and global harmonization.
Avionics manufacturers		Need standards to develop avionics. Standardization (form fit function) is a key issue.
		Cost, size, and weight are important metrics
		Customers don't want extensive retrofits
		Time to introduce technology 5-10 years.

Major Segment Category	Sub Category	Characterization
Government/regulatory /standards		Policy effected by politics, users are vocal
		FAA published plans to reduce VOR network, sustain and expand DME network, reduce CAT I ILS systems, maintain CAT II/III ILS (Until proven capability of augmented GNSS)

3.3.5.4 Round 1 Stakeholder Interview Results – Needs and Desired Features

Several stakeholder needs and desired features for the SatNav backup system were readily identified in the first round of interviews; many were voiced by several stakeholders. The drivers for a SatNav backup were frequently identified as both safety and the necessary economic capability to sustain continuing flight operations. The identified needs and desired features included the following:

- Performance requirements should be for an area navigation system (coordinate navigation system) like GPS.
- Performance should have similar, but not necessarily identical precision capability.
- Backup should provide a precision type of approach with a minimum capability of CAT I landing.
- Backup must support RNAV and RNP operations to/from supported airports.
- The cost/per airplane should be less than $100,000 and weigh less than 3 pounds (Regional air taxi).
- Cost, availability and reliability
- Cost and safety
- The backup has to meet the service requirements and ICAO SARPs integrity, availability, accuracy requirements, or declare a lesser class of service.
- Backup candidate should minimize radio spectrum requirements.

Additional stakeholder needs and desired features were derived through an analysis of the concerns and comments they expressed. These are summarized in Table 3-6. As shown in the table, some needs and desired features were prompted by similar concerns voiced by several stakeholders.

Table 3-6: Stakeholder Needs and Desired Features

Stakeholder Need or Desired Capability	Associated Stakeholder Comments and Concerns
SatNav backup equipage and/or transitional operational procedures must be ready to support aircraft performing precision landings with tight lateral separation.	*Safety when aircraft are operating with reduced spacing onto parallel runway approaches and SatNav capability is lost.*
	There is an increased concern if loss occurs during approach. This type of loss increases the catastrophic potential when considering missed approaches as an example.
A SatNav backup must sustain aircraft operations	*Long term (GNSS) outages could shut down NAV*

Stakeholder Need or Desired Capability	Associated Stakeholder Comments and Concerns
for an extended period of time.	*systems and create delays for the overall system.*
	Keeping aircraft on the ground is a significant cost, even if only a few hours. The cost implications increase if this lasts for several days. This would not be acceptable to commercial operators hence the need for a backup. (Cost in confidence of the consumer would be huge as well).
	We can manage the safety side; however a big driver is business continuity so we will make sure we can continue operations through long outages. We will not risk our business for short term savings on the chance that GPS will not be used
A backup strategy for surveillance is required in the event of ADS-B loss.	*As we move towards a greater dependence on ADS-B the implications of satellite navigation becoming unavailable are dramatic*
Backup system must be independent and not reliant on GNSS.	*For GNSS, a sole source and single point of failure should make anyone concerned*
Minimize user costs by not mandating early equipage but allow necessary retrofit at standard cycles.	*There are long cycle times to make upgrades and upgrades are expensive*
Seamless integration of a backup solution into avionics is required; else training for rollover to the backup is required.	*Our concern is what happens when the pilots that currently use moving maps for situational awareness and those that use electronic charts no longer have such technology if the system goes down. This could create safety of flight, security and terrain avoidance issues if those pilots, GA or other, are not familiar with old technology and how to quickly transition to using that old technology on a real-time basis*
	As we become more reliant on technology, what is the impact if we lose that technology and how do we ensure pilots are trained and proficient to lapse back to older technology? Training costs money and this drives many decision processes which may overlook safety issues such as these
U.S. policy should provide backup strategies for all segments of transportation. Preferable that SatNav backup assist other PNT needs as well.	*We need a backup applicable for all users of SATNAV. These include aviation, trucking and shipping. Timing is important*
	In terms of performance and cost, in today's world where the risk of terrorism needs to be taken into account, we can only hypothesize
SatNav backup should support NPA operations.	*If underlying Navaids are removed, minima are higher. Airfields without ILS would have to divert or not operate*
SatNav backup needs to be supported by new procedures, charts, (standards), and avionics equipage if not currently available.	*LORAN may give better coverage but its introduction into Europe would require the entire auxiliary element to be developed – procedures, rules, charts, publications (in addition to the equipment fit)*

3.4 REQUIREMENTS AND EVALUATION CRITERIA

For this study a set of evaluation criteria were needed as a key component of the Analytical Hierarchy Process described in Section 2. These criteria consisted of specific requirements and desired capabilities and characteristics for which candidate SatNav backup solutions could be assessed. The evaluation criteria also included a defined operational scenario to aid in the assessment of a candidate SatNav backup solution's ability to meet specified requirements.

Generally the requirements components of the evaluation criteria were derived from ICAO and RTCA aeronautical standards and are discussed in the next section. The rest of the evaluation criteria were distilled from the future navigation environment concepts described in Section 3.2 and from the future navigation needs and capabilities presented in Section 3.3, and are presented in Section 3.4.1.4.

3.4.1 Requirements Based Evaluation Criteria

3.4.1.1 Introduction - Performance Based Navigation

The essence of the PBN concept is presented in the ICAO's *Performance Based Navigation Manual*.[27] That document summarizes PBN concepts as follows[28]:

> The PBN concept specifies aircraft RNAV system performance requirements in terms of accuracy, integrity, availability, continuity and functionality needed for the proposed operations in the context of a particular Airspace Concept. The PBN concept represents a shift from sensor-based to performance-based navigation. Performance requirements are identified in navigation specifications, which also identify the choice of navigation sensors and equipment that may be used to meet the performance requirements. These navigation specifications are defined at a sufficient level of detail to facilitate global harmonization by providing specific implementation guidance for States and operators.
>
> Under PBN, generic navigation requirements are defined based on the operational requirements. Operators are then able to evaluate options in respect of available technologies and navigation services that could allow these requirements to be met. The chosen solution would be the most cost effective for the operator, rather than a solution being imposed as part of the operational requirements. Technologies can evolve over time without requiring the operation itself to be revisited, as long as the requisite performance is provided by the RNAV system.
>
> Within an Airspace Concept, PBN requirements will be affected by the communication, surveillance and ATM environment, as well as the Navaid infrastructure and the functional and operational capabilities needed to meet the ATM application. PBN performance requirements will also depend on what reversionary, non-RNAV means of navigation are available and hence what degree of redundancy is required to ensure an adequate continuity of function.

[27] *Performance Based Navigation Manual*, ICAO Special Operational Requirements Study Group (RNPSORSG), Working Draft 5.1-FINAL, 7th March 2007.
[28] Ibid. pp. ii – iii.

3.4.1.2 RNAV Required Functions

According to ICAO and RTCA, an RNAV system must provide the following four basic functions[29]:

- Navigation (position estimation)
- Flight plan management (path definition)
- Guidance and control (path steering)
- Display and system control (situation indications and alerting)

The interrelation of these functions is shown in Figure 3-9.

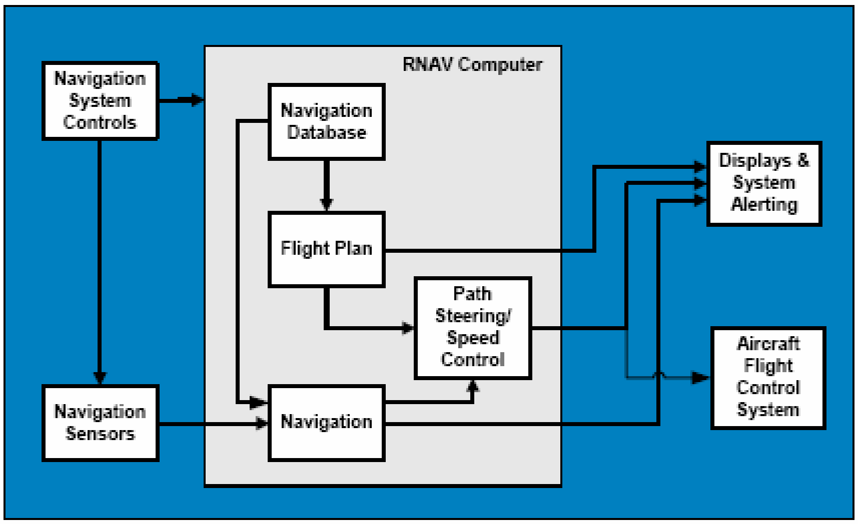

Figure 3-9: RNAV Basic Functions[30]

These high level functions are required for all SatNav backup solution candidates.

3.4.1.3 Navigation Performance Requirements

The derived performance requirements for aircraft operating in managed air space are based both on the *method* of navigation and the statement of navigation performance necessary to operate within a defined air space. RNAV (area navigation) is a *method* of navigation that permits aircraft operation based user desired flight paths and is defined by geographic waypoints, expressed by latitude and longitude. This is contrasted with traditional flight routes that would require aircraft to over fly ground based navigation aids. The desired flight paths with the RNAV method must be within the coverage of reference navigation aids (NAVAID) or within the capability of self contained systems.

Required Navigation Performance (RNP) describes the navigational performance accuracy necessary for operation within a defined airspace. RNP is RNAV operations with onboard navigation performance

[29] In each case the first term is the PBN Manual term and the second comes from DO-236B
[30] *PBN Manual*, Volume I, Attachment A – Page 3

monitoring and alerting. The term RNP can describe an airspace, routes, and procedures. These procedures can include terminal area departures, arrivals, and instrument approaches.

A Navigation Specification, as defined in the ICAO PBN Manual, details what performance is required of the RNAV system in terms of accuracy, integrity, availability, and continuity. A PBN specification is either a RNP specification or a RNAV specification, and includes the accuracy requirement for lateral and longitudinal directions (see Figure 3-10). For both RNP-x and RNAV-x designations the expression "x" refers to lateral navigation accuracy in nautical miles that is expected to be achieved at least 95 % of the flight time (see Figure 3-11). The value of "x" is the lateral total system error (TSE).

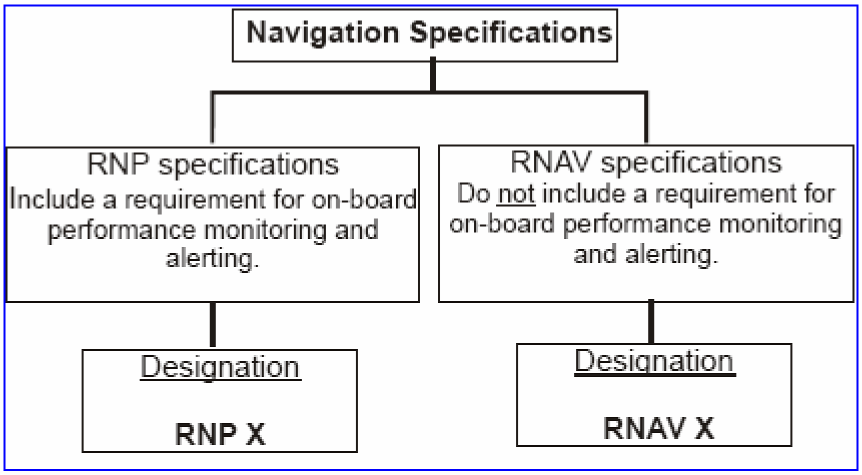

Figure 3-10: Navigation Specifications[31]

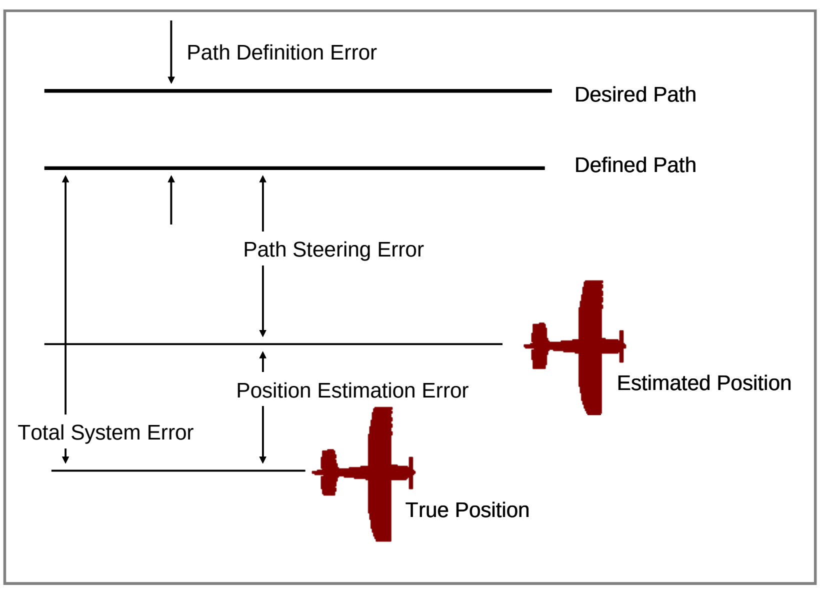

Figure 3-11: Lateral Components of Navigation Error Terms[32]

[31] ICAO *PBN Manual*, Vol. I, p. A-1-3.

In addition to navigation *accuracy* requirements, navigation *integrity* and *continuity* performance requirements also have been specified for RNP airspace and are defined as follows:

- The integrity performance requirement refers to the probability that the total system error of the aircraft operating in RNP airspace[33]exceeds the specified lateral (cross track) containment limit *without annunciation*. Both the ICAO *PBN Manual* and DO-236B specify $<10^{-5}$ per hour for RNP integrity performance.
- Continuity performance requirements
  - The continuity performance requirement specified in DO-236B is: the probability of *annunciated* loss of RNP capability shall be less than 10^{-4} per flight hour
  - In the ICAO *PBN Manual* the continuity requirement refers to the *Performance Monitoring and Alerting* requirement that the RNP system, or RNP system and pilot in combination, shall *provide an alert* if the accuracy requirement is not met, or if the probability that the lateral TSE exceeds two times the lateral (cross track) total system error is greater than 10^{-5}.

According to the *Roadmap for Performance-Based Navigation*, the FAA has targeted the following RNP levels as its near to mid-term performance goals:

- RNP<2 for en route
- RNP<1 for terminal (standard approaches and departures)
- RNP<0.3 for non precision approach operations

These were selected as threshold requirements and evaluation criteria for the SatNav Backup Study.

3.4.1.4 Other Requirements Based Evaluation Criteria

3.4.1.4.1 Failover Functional Requirement

The failover process from the primary satellite navigation system to the backup system should be seamless and result in the backup system meeting specified performance requirements (as defined above for RNP). A seamless failover means that when failover to the backup system is required, no immediate crew or ground service provider action is necessary. If the backup system performance degrades with time, a further consideration of a backup solution's capabilities would be the expected duration of performance compliant operation.

3.4.1.4.2 Defined Operational Scenario Based Evaluation Criteria

A functional requirement defined by the study team considered the scenario of a terminal area disruption to satellite navigation capability. In this scenario, an aircraft with satellite navigation in en route air space would experience satellite navigation disruption in the terminal area. The capabilities of a backup system to enable RNP-1.0 operations, or more restrictively to enable RNP-0.3 non precision approaches

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[32] Adapted from Figure 1-2 in RTCA DO-236B, *Minimum Aviation System Performance Standards: Required Navigation Performance for Area Navigation*, October 28, 2003

[33] RTCA DO-236B refers to this as "RNP RNAV" airspace.

were both evaluated. The ability to perform departure procedures to reach en route air space is also considered. The affected radius of interference was assumed to be 40-60 nm.

3.4.2 Non-Requirements Based Evaluation Criteria

In addition to the evaluation criteria defined in Section 3.4.1, additional criteria identified through review of future navigation environment concepts and consideration of the future navigation needs and capabilities (including inputs from stakeholder surveys) were defined. They include the following items:

- Technical readiness in 2015-2025
- Independence of backup system from GNSS
- Low user life cost
- Low infrastructure provider life cycle cost
- Near global support
- Available, reliable and small size & weight avionics
- Safe transitions between primary and back-up operations
- Support area navigation (latitude/longitude) like GPS
- Minimum radio spectrum requirements
- Sustain aircraft operations for an extended period of time
- Support navigation needs for other segments of transportation and other US PNT needs as well

3.4.3 Summary of Evaluation Criteria

Table 3-7 lists the full set of requirements and desired capabilities that served as the evaluation criteria for this study.

Table 3-7: Evaluation Criteria

Requirements and Desired Capabilities	
Technical Requirements	≤ RNP-2.0 en route
	≤ RNP-1.0 terminal
	RNP-0.3 NPA
Functional Requirements and Capabilities	Technical readiness in 2015-2025
	Backup system must be independent and not reliant on GNSS.
	Seamless failover for aircraft
	Seamless failover for air traffic control
	Navigate through terminal area SatNav disruption maintaining RNP-1.0 to the approach (minimum)
	Navigate through terminal area SatNav disruption maintaining RNP-1.0 to the approach and perform a RNP-0.3 NPA
	Low user life cost (desired characteristic)
	Low infrastructure provider life cost (desired characteristic)
	Near global support (goal)

Requirements and Desired Capabilities	
	Available, Reliable, Small Size & weight
	Safe transitions between primary and back-up operations
	Support area navigation (latitude, longitude) like GPS
	Minimize radio spectrum requirements
	A SatNav backup must sustain aircraft operations for an extended period of time.
	The backup strategy should support navigation needs for all segments of transportation and other US PNT needs as well.

To support application of the evaluation criteria in this assessment, they are organized into a hierarchical structure. This provides a means to identify unique sets of criteria and meaningful groups for which the relative importance between the groups of criteria can be assessed. Each group of criteria makes up a branch of what is called the *decision factor hierarchy*, where the group/branch names are called global (or Level-1) evaluation decision factors. The organization of criteria derived above into a decision factor hierarchy to be applied in this study are shown in Figure 3-12.

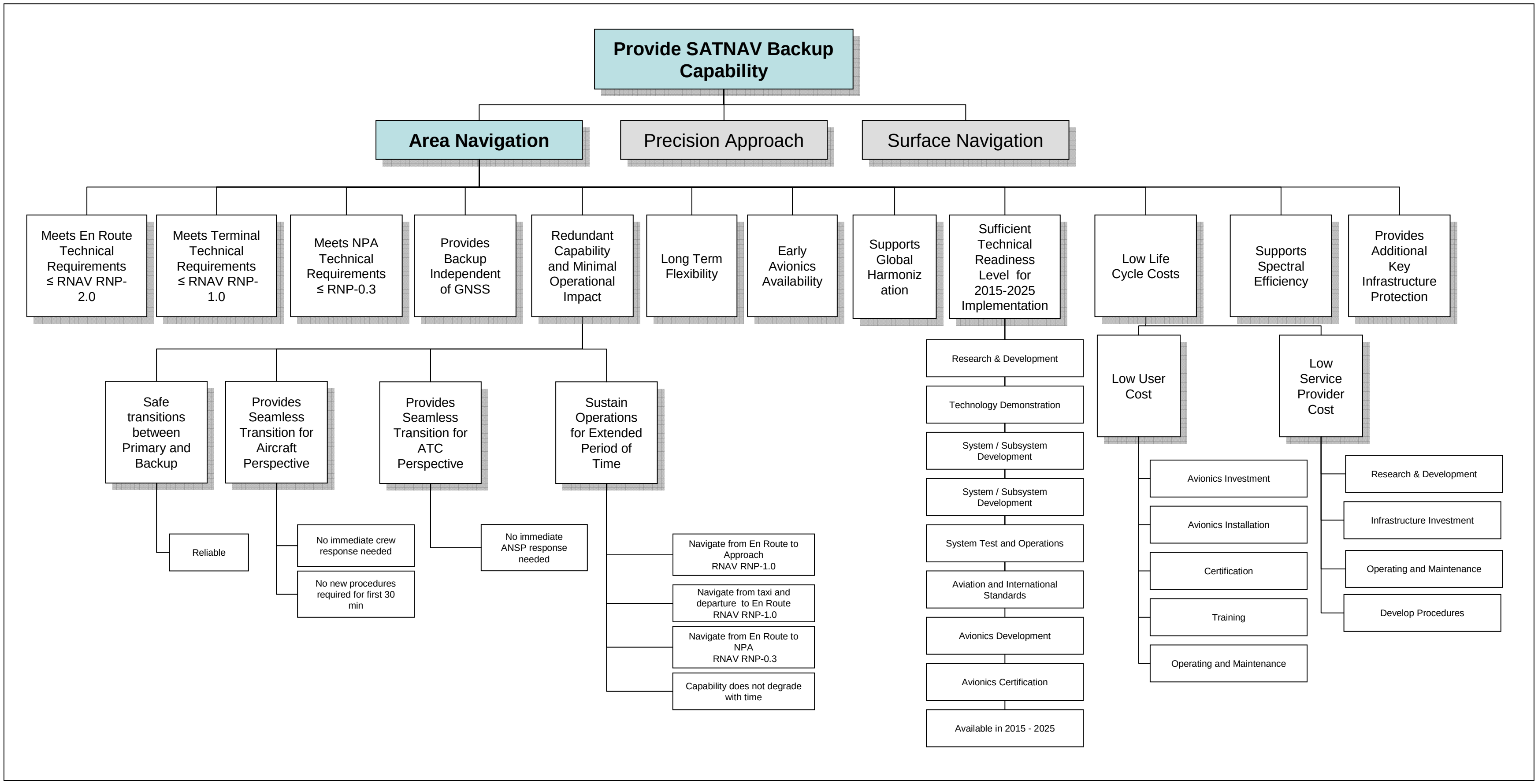

Figure 3-12: SatNav Backup Evaluation Criteria Functional Hierarchy

Note: Potential SatNav backup candidates for Precision Approach and Airport Surface Navigation phases of flight activity are discussed in the appendices.

Five of the top-level decision factors/evaluation criteria[34] in the hierarchy above are directly related to technical requirements or are very straightforward in terms of the criteria definition. These include:

- ≤ RNP-2.0 en route
- ≤ RNP-1.0 terminal
- ≤ RNP-0.3 non precision approach
- Technical Readiness in 2015-2025
- Provide backup independent of GNSS

No further elaboration of these decision factors is provided. For the seven other top-level decision factors, many are a roll-up of several lower level evaluations factors and a clear definition of what the decision factor means when applied in this study is needed. This subset of top-level decision factors is provided in Table 3-8. Several of these factors are discussed in greater detail in the following paragraphs.

Table 3-8: Subset of Key Decision Factors/Evaluation Criteria with Definitions

Decision Factor	Description of Stakeholder Value
Low Life Cycle Costs	Values low life cycle costs to the users and the infrastructure provider to provide and maintain a SatNav backup system
Long Term Flexibility	Values flexibility in adapting to changing needs without significant reinvestments
Redundant Capability and Minimal Operational Impact (Seamless Failover)	Values near equivalent navigation performance to that of the primary Satellite Navigation system, and also that when required, the failover is seamless, with no exceptional crew or ground actions required
Early Avionics Availability	Values the early availability of avionics for the SatNav backup
Global Harmonization	Values the near global support of a determined SatNav backup
Spectral Efficiency	Values the efficient use of aeronautical radio spectrum
Additional Key Infrastructure Protection	Values that the SatNav backup system would also benefit other key aviation and national infrastructure Position, Navigation, and Timing (PNT) requirements

3.4.3.1 Low Life Cycle Costs

This factor values low life cycle costs to the users and the infrastructure provider to provide and maintain a SatNav backup system.

3.4.3.2 Long term Flexibility[35]

This factor values solutions that are flexible in adapting to changing needs without significant reinvestments. For example, the SatNav backup should easily accommodate evolutionary changes to the

[34] The terms *key decision factors* and *evaluation criteria* are identical in meaning and are interchangeable for this study. The AHP mainly uses *key decision factors*.

performance based navigation requirements. Such requirements, driven by increases in traffic density and decreases in separation distances, should be accommodated with minimal additional cost to both infrastructure support and users. Support for non precision approaches added to airports should be accommodated without major redesign or expansion of ground aid systems.

3.4.3.3 Redundant Capability and minimal Operational Impact

With different SatNav backup systems, there are a range of capabilities with different operational issues. This factor values the navigation capability of the backup that enables near equivalent navigation performance as with the primary Satellite Navigation, and also that when required, the transition to the backup (failover) is seamless, with no exceptional crew or ground actions required. This factor also places value to solutions that do not have performance degradation over time.

3.4.3.4 Early Avionics Availability

Some backup system solutions for the period of 2015-2025 and beyond may not have available equipage in the near term. An example would be a solution implementing a new technology. This factor values the early availability of avionics for the SatNav backup. It was assumed that other backup solutions using traditional navigation aids would support the needs of users until the proposed backup avionics are available.

3.4.3.5 Global harmonization

This factor values the global[36] support of a determined SatNav backup solution. Global harmonization requires international standards and participating regions must commit to necessary investments to build, operate, and maintain any required ground aids. This factor is expected to be particularly important to international carriers wanting to minimize avionics equipage.

3.4.3.6 Spectral Efficiency

This factor values the efficient use of aeronautical radio spectrum. The need for allocation of this scarce resource to important future aviation voice and data needs is a concern recognized by the stakeholders.

3.4.3.7 Additional Key Infrastructure Protection including ADS-B[37]

This factor values that the SatNav backup system would also benefit other key aviation and national infrastructure that rely on Position, Navigation, and Timing (PNT) services.

As evidenced in the Volpe GPS Vulnerability Assessment Report, adoption of GPS as key infrastructure for critical applications such as aeronautical navigation (e.g. for GNSS SatNav) and surveillance (e.g. for

[35]‘ Long term flexibility’ is similar to the ‘adaptability’ evaluator used in the national PNT Architecture Development Team activity.
[36] The term global is not intended to include oceanic regions where the only navigation aid for satellite navigation backup is an inertial navigation system.

Automatic Dependent Surveillance – Broadcast (ADS-B)) has definable risks. Insofar as loss of GPS functionality presents a single point of failure to multiple applications, a judiciously selected backup solution developed and implemented for one application would fortuitously provide a similar backup function for all other applications dependent on the same primary system. This is well understood and a motivation for the need to ensure that candidate SatNav backup solutions are suitable for backing up ADS-B services in the event of a GPS disruption affecting both services.[38]

ADS-B is a surveillance concept where cooperating aircraft (or other vehicles or obstacles) regularly broadcasts a message, which includes their position (such as latitude, longitude and altitude), velocity, and possibly other information. The FAA plans to implement ADS-B via the Surveillance Broadcast Services Program that will include four services: ADS-B, ADS – Rebroadcast (ADS-R), Traffic Information Services – Broadcast (TIS-B), and Flight Information Services – Broadcast (FIS-B). ADS-B is a key enabler of NextGen concepts, particularly for shared situational awareness.

ADS-B systems are dependent on input navigation signals to provide reference timing and position information. Though ADS-B systems will be able to operate with input navigation sources of varying accuracy and integrity, the quality of the surveillance services capable of being provided by an ASD-B system is directly dependent on the quality of the available input navigation signals. Two parameters: Navigation Accuracy Category for Position (NAC_p) and Navigation Integrity Category (NIC) are used by surveillance applications such as ADS-B to determine whether reported geometric position input from the navigation system is of acceptable quality (i.e. accuracy or integrity) for its intended use. Table 3-9 lists the possible values for NAC_p and the associated navigation performance category associated with each one.

Table 3-9: Navigation Accuracy Categories for Position (NAC_p)[39]

NAC_p	95% Horizontal and Vertical Accuracy Bounds (EPU[3] and VEPU[4])	Comment	Notes
0	EPU ≥ 18.52 km (10 NM)	Unknown accuracy	1
1	EPU < 18.52 km (10 NM)	RNP-10 accuracy	1
2	EPU < 7.408 km (4 NM)	RNP-4 accuracy	1
3	EPU < 3.704 km (2 NM)	RNP-2 accuracy	1

[37] ADS-B is considered but not fully analyzed in this Study. A more complete analysis can be found in *Surveillance/Positioning Backup Strategy Alternatives Analysis* Final Report, FAA, January 8, 2007.
[38] This was a similar consideration in the *Surveillance/Positioning Backup Strategy Alternatives Analysis* Final Report, FAA, January 8, 2007, where "potential applicability to navigation services/operations" was one of the flexibility metrics used for that study.
[39] *Minimum Aviation System Performance Standards for Automatic Dependent Surveillance Broadcast (ADS-B)*, RTCA DO-242A, 2002, p. 39. The NAC_p 8 and 9 Comment fields are modified to eliminate RTCA reference to SA, since the U.S. has expressed assurances that it has no intent to use this feature and to remove SA capabilities in future GPS III satellites.

NAC_p	95% Horizontal and Vertical Accuracy Bounds (EPU[3] and VEPU[4])	Comment	Notes
4	EPU < 1852 m (1 NM)	RNP-1 accuracy	1
5	EPU < 926 m (0.5 NM)	RNP-0.5 accuracy	1
6	EPU < 555.6 m (0.3 NM)	RNP-0.3 accuracy	1
7	EPU < 185.2 m (0.1 NM)	RNP-0.1 accuracy	1
8	EPU < 92.6 m (0.05 NM)		1
9	EPU < 30 m and VEPU< 45 m	e.g., GPS	2
10	EPU < 10 m and VEPU< 15 m	e.g., WAAS	2
11	EPU < 3 m and VEPU< 4 m	e.g., LAAS	2

Notes:
1. RNP accuracy includes error sources other than sensor error, whereas horizontal error for NAC_p only refers to horizontal position error uncertainty.
2. If geometric altitude is not being reported, then VEPU tests are not assessed.
3. EPU = Estimated Position Uncertainty
4. VEPU = Vertical Estimated Position Uncertainty

It should be noted that the "NAC_p for a TIS-B target will be based on the surveillance sources used to derive the target position rather than navigation sources used to supply ADS-B position"[40]; in other words, because TIS-B (an essential service) does not rely on navigation system sources, GPS outages would not affect TIS-B services accuracy. ADS-B systems, which do receive position information from navigation sources, can accommodate NAC_p up through 11 to support precision surveillance applications[41], while ADS-R systems are limited to NAC_p values of 9.[42]

Based on the foregoing discussion, it is evident that backup of surveillance systems will require a system of the same level of performance as the SatNav backup system. The Surveillance/Positioning Backup Strategy Alternatives Analysis team had an intermediate position accuracy metric of 0.3 nm[43]. The solution recommended by the surveillance backup team is a Secondary Radar backup strategy, which provides 0.72 nm positional accuracy for en route operations and 0.17 nm positional accuracy for terminal operations.

[40] *Traffic Information Service – Broadcast (TIS-B)/Flight Information Service - Broadcast (FIS-B) Essential Services Specification*, Version 1.1, U.S. Department of Transportation Federal Aviation Administration Surveillance and Broadcast Services Program, 4 April 2007, p. 24.
[41] *Automatic Dependent Surveillance-Broadcast (ADS-B)/ADS-B Rebroadcast (ADS-R) Critical Services Specification*, Version 1.2, U.S. Department of Transportation Federal Aviation Administration Surveillance and Broadcast Services Program, 12 April 2007, p. 21.
[42] Ibid. p. 44.
[43] *Surveillance/Positioning Backup Strategy Alternatives Analysis Report*, p. 13.

4. BACKUP ALTERNATIVES DEFINITION AND INITIAL SCREENING

The preceding section identifies the criteria that will be considered for evaluation of SatNav backup solutions for the area navigation operations. The first several steps in the applied methodology to perform this evaluation, as shown in Figure 4-1, include the definition of threshold criteria; identification of SatNav backup alternatives; and then screening the alternatives to determine candidate solutions for further evaluation. This screening process is the topic of this section. It includes:

- Section 4.1: Identification and Description of Area Navigation Alternatives
- Section 4.2: Identification of Threshold Criteria for Screening
- Section 4.3: Screening Alternatives to Identify Applicable Backup Candidates

4.1 IDENTIFICATION & DESCRIPTION OF AREA NAVIGATION ALTERNATIVES

4.1.1 Identification of Alternatives

The identified alternatives to provide satellite navigation backup for area navigation is a collected set of NGATS Institute mandates, stakeholder additions, and project study team additions. Specifically, the process applied to identify candidates is shown in Figure 4-1 below.

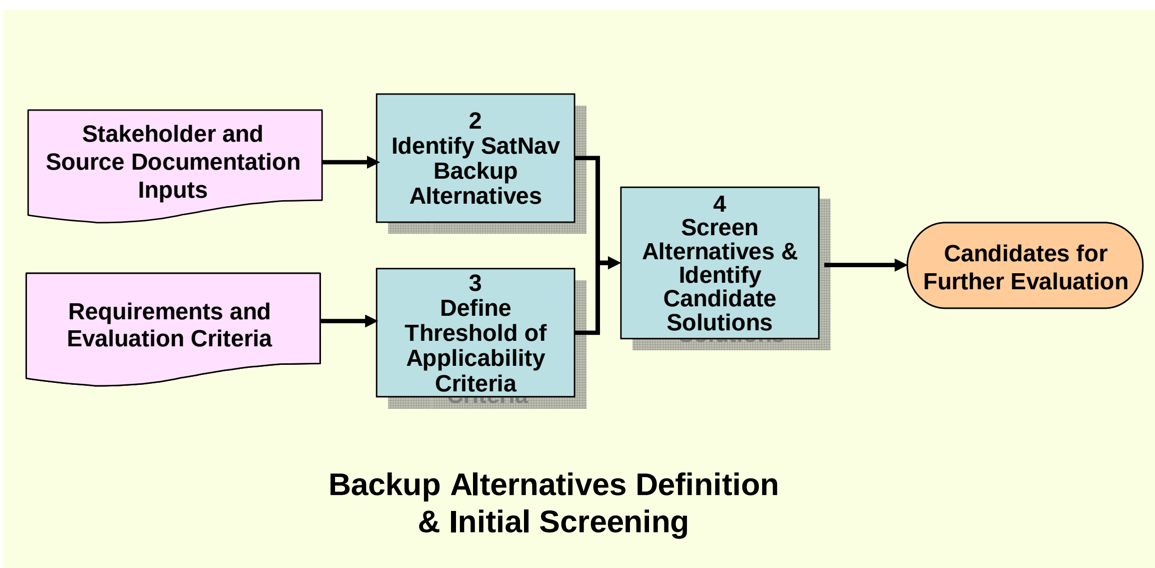

Figure 4-1: Process for Identifying Backup Alternatives

The following SatNav backup system candidates for Area Navigation were derived from technologies mandated for consideration by the NGTAS Institute:

- DME/DME/INS,
- GNSS/INS: Inertial Navigation System updated by GNSS (when available), and
- eLORAN

This list was supplemented by the results of the Round 1 stakeholder interviews, described in Section 3. In addition to the mandated candidates already under consideration, stakeholders suggested one additional system for consideration for area navigation[44]: the Very High Frequency (VHF) Omni Directional Range (VOR) navigation system. Comments of stakeholders specific to each of the candidates identified are captured in Table 4-1. Note that these comments should not be interpreted as general stakeholder consensus, but rather as independent views.

Table 4-1: Comments on Alternatives Received from Stakeholders

Stakeholder Identified Alternatives for Backup	Stakeholder Comments
VOR	"80%-90% of GA aircraft are currently equipped with VORs. Small aircraft cannot install INS systems"
eLORAN	"LORAN is a suitable backup. Also satisfies other PNT needs."
Hardened GNSS system	"I am aware of only two proposed backup solutions that would allow similar functionality as current SatNav: (1) eLORAN or (2) a redundant hardened GNSS system. … Nearly equivalent RNP functionality."
ILS or MLS	"If GNSS is used for final approach, then cannot see us moving away from ILS as the primary precision approach system."
	"MLS offers some potential benefits"
Ground radar and ground air traffic control providing vectors. Also needs ILS.	"In the event of a failure recovery by radar means is feasible."
DME/DME/INS	"INS is a capable system in terms of the graceful way it degrades. It's the most credible option in terms of the safety element. DME and INS/FMS are currently fulfilling this role."
	"Full coverage by DME/DME would meet all the requirements for 4-D trajectories. The problem is, achieving full coverage; there would have to be an increase in the number of DMEs and there would be a corresponding increase in frequency congestion. Today's DME service is acceptable, except for approaches in low visibility conditions."

The third major input for definition of backup alternatives resulted from the review of required functional characteristics and requirements for a backup system described in Section 3 and review of

[44] As shown in the table, some stakeholders mentioned backup solutions for precision approaches.

related studies by the assessment study team. Based on these reviews, the following additional candidates were identified for satellite navigation backup for RNAV:

- Hardened GNSS system
- Terrain reference navigation system
- Multilateration system

In summary, the full set of alternatives considered at this stage of the study is listed in Table 4-2 below.

Table 4-2: SatNav Backup Alternatives for Area Navigation

	Area Navigation SatNav Backup Candidate	Contributor
1	DME/DME/INS	Mandated and from stakeholders
2	eLORAN	Mandated and from stakeholders
3	GNSS/INS	Mandated and from stakeholders
4	VOR	Stakeholders
5	Hardened GNSS system	Study team
6	Terrain reference navigation system	Study team
7	Multilateration system	Study team

4.1.2 Description of Alternatives for Area Navigation

As noted above, seven alternative candidate SatNav backup solutions for area navigation were identified for consideration in this study. An overview of each system is provided in the following subsections.

4.1.2.1 DME/DME/INS

A Distance Measuring Equipment (DME) system consists of an interrogator onboard the aircraft and a transponder located at a ground station. At regularly spaced intervals, the interrogator transmits coded pulse signals. The transponder receives the signals and transmits a coded response signal. The aircraft receives this signal, computes the elapsed time, and determines the slant range distance from the ground station. When multiple DME ground stations are in range (denoted as DME/DME), the aircraft can derive its position. A DME/DME navigation system integrated with an inertial reference unit becomes DME/DME/INS.

For RNAV operations, FAA *AC 90-100A*, *U.S. Terminal and En Route Area Navigation (RNAV) Operations*[45], defines the minimum DME/DME/INS system baseline performance. With the accommodating supporting infrastructure, DME/DME/INS RNAV systems are capable of RNAV-

[45] *U.S. Terminal and En Route Area Navigation (RNAV) Operations*, FAA Advisory Circular AC 90-100A, 03/01/07.

2.0 en route and RNAV-1 SIDs and STARs terminal procedures. In most existing aircraft, the Flight Management System (FMS) operates in a DME/DME mode when a position from the ground aids can be derived. The inertial capability allows the DME/DME/INS system to coast when a position determination from ground DME Navaids is not available. This effectively allows the DME/DME/INS to coast while crossing gaps in DME/DME coverage.

Appendix 1 of *AC 90-100A* specifies minimum requirements that must be satisfied relative to distance and elevation above the DME ground station for a DME signal to be available for use. Also, a suitable geometry between ground stations and the aircraft is necessary for reduce position uncertainty. Multiple stations satisfying these requirements are not always in view for RNAV operations. The RNAV navigation system must automatically update the INS when valid DME/DME positioning is derived. The coasting inertial unit then provides the capability for sustaining navigation between areas where a DME/DME position determination cannot be made.

AC 90-100A references Federal Air Regulations in 14 CFR Part 121 Appendix G to provide the required performance for inertial systems. This regulatory document requires that the inertial system following alignment must have (95%) accuracy within a growing error bound of 2 nm / hr for flights less than 10 hours. In *AC 90-100A***,** Appendix 2, a note reads:

> *"Based on an evaluation of IRU[46] performance, the growth in position error after reverting to IRU can be expected to be less than 2 nm per 15 minutes."*

RTCA/DO-283A, Minimum Operational Performance Standards for Required Navigation Performance for Area Navigation, Appendix C.3.1.3 requires the inertial navigation system after initialization and loss of radio updates to provide at least the accuracy shown in Table 4-3, where T is the time on coast since the last radio update.

Table 4-3: INS Positioning Error Growth

Time Since Radio Updating (T) (hr)	IRS 95% Error (NM)
0.0 to 0.5 hr	8*T
0.5 to 1.5 hr	4

Other studies[47] indicate that highest quality inertial system can have lower 0.6 nm/hr drift rates. Drift rate relates to available coast time while still maintaining performance capability required by an airspace. Figure 4-2 illustrates the (95%) error bounds that are determined by the different standards or assumptions. These bounds are recognized as optimistic in that the last DME/DME position estimate fix would also carry statistics of expected accuracy, based on a number of specific factors including the aircraft to DME distances and their geometries relative to the aircraft.

[46] Inertial Reference Unit (IRU) in the quote and as appears in *AC 90-100A* is equivalent with INS
[47] *GPS Backup for Position, Navigation, and Timing; Transition Strategy for Navigation and Surveillance*, Lilley, Church, and Harrison (Aviation Management Associates, Inc), for FAA, Aug 22, 2006.

The retention of DME ground stations through 2020 are part of both the U.S. Federal Radionavigation Plan. It notes further that an expansion of the DME network may be required to support RNAV in terminal area operations at major airports and to provide continuous RNAV operations at en route altitudes.

DME/DME/INS is common equipage for U.S. and European Air Carriers. DME/DME is the assumed SatNav backup strategy for European states. With adequate DME infrastructure, DME/DME/INS equipage enables users to satisfy RNAV 2 en route and RNAV 1 terminal area performance requirements. Before the FAA publishes new DME/DME and DME/DME/INS routes, it ensures that sufficient DME station infrastructure is available to enable users to meet the appropriate requirements.

The air taxi and other commercial segments of General Aviation are likely to have equipage with DME/DME integrated into a flight management system. It is less common for this segment to equip with inertial systems. With DME/DME systems without inertial systems, the aircraft will not satisfy the performance requirements of routes and procedures outlined in *AC 90-100A.*

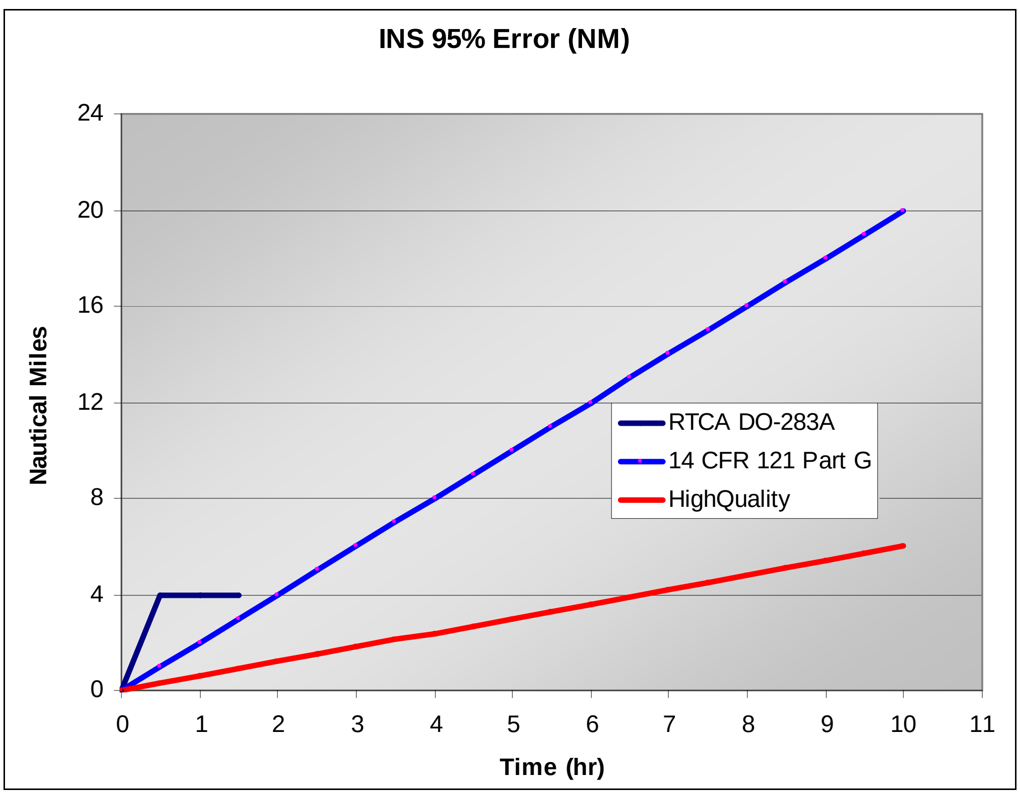

Figure 4-2: Inertial Error Bounds[48]

The JPDO expects higher RNAV and RNP performance requirements in 2025. The primary SatNav system will enable navigation systems to achieve these higher performance requirements. However, higher requirements will place heavy demands on a SatNav backup system. For DME/DME solutions, this will require possible relocation and expansion of DME stations, primarily in terminal areas. DME placement is seldom available to support the RNP-0.3[49] non precision approach requirements. DME/DME/INS capabilities can be improved through the following:

- Expansion of the ground DME network
- Improved inertial system capabilities to allow longer coast times
- FMS systems that use all-in-view DME solutions

4.1.2.2 eLORAN

Many recent studies have assessed the role that eLORAN (enhanced Long Range Navigation) could serve as a PNT backup strategy to protect the U.S. infrastructure in the event of the loss of GPS. Federal Policy decisions are pending concerning whether eLORAN modernization will be completed and the system maintained, or if it will be decommissioned. There are strong proponents on each side of this argument. This study assumed that a policy decision will be made to fund eLORAN with a commitment through at least 2025.

Other reports[50] present the rationale of the modernized eLORAN and detail the design and operational differences from its predecessor LORAN-C. The potential benefits to key infrastructure apart from aviation navigation are well understood by stakeholders interviewed in this study. Its capability as a Stratum 1 timing and frequency reference signal could protect vital assets including telecommunication systems and other systems that derive precision reference from GPS. This section will focus on eLORAN relative to its capabilities in serving as a SatNav backup solution

eLORAN transmits at high power levels in the 90 - 110 kHz spectrum. The resultant ground wave transmission signals effectively range to 1000+ miles. Efficient transmission at this frequency requires a long antenna length and LORAN towers are typically 200+ m high. The power levels may exceed 1000 kW. These transmitted power levels result in received signal strengths much higher than GPS levels, and the physics of effective transmission at these frequencies make eLORAN particularly difficult to intentionally jam.

These same physical characteristics, together with atmospheric or weather phenomena, sometimes cause the transmission path to be influenced by an effect called indirect sky wave. The result is multiple signal paths that can make signal reception difficult. A secondary physical limitation is

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[48] Note that error bound found in 14 CFR 121 Part G and for the ‘high quality’ case are based on an initial ground alignment. The error bound found in RTCA DO-283A would be based on time since last update.

[49] The only practical way for DME/DME to support RNP-0.3 is to significantly increase the density of ground facilities and to replace existing FMS with systems that use all-in-view DME solutions.

[50] Appendix A reference list, LORAN

that the ground wave propagation speed is determined by the conductivity of the earth. Slight variations that are uncorrected can result in position errors in the 100s of meters[51] from absolute position. The good news is that the repeatable accuracy is in the 18-90 m[52] range. With a correction factor determined for a location and applied to the "distance from the transmitter" calculation, the predictable accuracy is significantly improved. Current studies are determining the merit or need to modify these correction factors on an annual, seasonal, or more frequent basis.

Table 4-4 and Table 4-5 list eLORAN assumptions for this study.

Table 4-4: eLORAN Assumptions

Phase of Flight Operation	eLORAN Assumption
En route	Without needing correction factors, eLORAN accuracy is sufficient to enable RNP-2.0 en route requirements
Terminal SIDs and STARs	Either: • a single correction factor could be applied to a terminal area, or • a grid of correction factors could be applied over the terminal area to enable RNP-1.0 terminal SIDs and STARs procedures.
Non Precision Approach	A single correction factor at the final approach, periodically corrected if necessary, will enable RNP-0.3 non precision approach operations for a runway

Table 4-5: eLORAN Assumptions for 2025 Navigation Requirements

Navigation requirements	eLORAN Assumption
FAA *Roadmap for Performance Based Navigation* (July, 2006)	An eLORAN system is capable of meeting all projected 2025 RNAV and RNP requirements for en route, terminal, and non precision approach operations.

An eLORAN based navigation system also has benefits in flexibility for the infrastructure provider in that is can readily accommodate changes in airspace classification likely to occur through 2025 without reconfiguring or adding ground support stations.

With added LORAN monitoring stations, differential correction can be applied to enable maritime users to achieve Harbor Entrance and Approach (HEA) accuracy requirements of 20 m and Horizontal Protection Limit of 50 m[53]. The application of differential correction methods for aviation could potentially improve accuracy at areas of interest such as airports and their environs. The required monitoring stations and the systems to disseminate correction data to aviation users do not exist.

[51] Predictable error of LORAN-C is 460 m (95%) from FAA *LORAN's Capability to Mitigate the Impact of a GPS Outage on GPS Position, Navigation, and Time Applications*.
[52] Repeatable accuracy of LORAN-C (95%), same reference.
[53] Ibid.

The eLORAN signal structure includes a data channel. Early sky wave detection warning is an important content of the data channel and enables eLORAN receivers from using hazardously misleading information (HMI) in their position determination. This is an important addition with eLORAN modernization and enables aviation users to satisfy the integrity requirements for navigation. The data channel has sufficient capacity to also transmit the differential correction information to the maritime users at the major U.S. ports. The obvious advantage to users is that only a single receiver is required for both the signal and data. If eLORAN were to be considered for supporting navigation requirements < RNP-0.3, a differential eLORAN concept, considerable additional infrastructure, and more complicated and costly user equipage may be required.[54]

The establishment of precise Stratum 1 clocks with each eLORAN transmitter and other operational changes improve the coverage and continuity of the signals for users. By decoupling the concept of chains[55], users have more eLORAN signals of opportunity for use. The eLORAN modernization strategy is in progress and when complete in 5-8 years will add four transmitters and improve coverage.[56] The LORAN transmitting locations and the projected coverage of eLORAN are illustrated in Figure 4-3.

Figure 4-3: eLORAN Coverage with Cooperative International Policy[57]

[54] Study recommendations in Section 7.2 include the consideration of development of a Low Frequency PNT system with performance and data handling capability improvements above eLORAN.
[55] Termed all-in-view in eLORAN literature.
[56] *Independent Assessment Team (IAT) Summary of Initial Findings on eLORAN*, presentation to DOR & DHS POS-NAV Executive Committees, 20 March 2007, Washington D.C.
[57] Map released into public domain, ref http://en.wikipedia.org/wiki/Image:LORANCoverage.gif

eLORAN coverage will include the CONUS and most of Alaska. LORAN infrastructure is also operated in Europe, northern Russia, and the Asia Pacific basin. The U.S. and these regions are facing policy decisions concerning the continuation of LORAN services. Other nations and regions will be looking closely for U.S. leadership.

User avionics equipage is an issue for implementing eLORAN based navigation. Due to the significant advantages of SatNav, avionics system manufacturers have not built LORAN receivers for aviation for over a decade. U.S. Policy that has presented numerous decision points for considering system decommissioning has further sidelined interest in LORAN system development. All existing equipage will be based on the prior LORAN-C system. Even though the eLORAN signal may be backward compatible to LORAN-C receivers, the older receivers will not be able to take advantage of the significant eLORAN modernization advances. LORAN-C receivers usually linked to General Aviation. An issue in the retrofit to eLORAN system will be the new antenna requirements and cabling.

In Europe there is negligible equipage with LORAN receivers. Aviation stakeholders are aware of the eLORAN interest in the U.S. From the stakeholder interview responses, there is a strong presumption that the European SatNav backup strategy will be DME and ILS. We noted skepticism that even if Europe were to commit to an eLORAN type modernization, it would be done for maritime users and to backup other PNT assets and would not be implemented by aviation. There was however, a “wait and see” attitude.

Early eLORAN avionics developers see a tight integration where a common system receives both GPS and eLORAN signals. Prototype systems have demonstrated the application of a common antenna assembly and a modular receiver. Figure 4-4 illustrates this simple architecture of an avionics assembly with GPS and eLORAN integrated and sharing common control and display units. Early working prototypes use an additional card to implement the eLORAN portion of the receiver. High production volumes would likely take advantage of Application Specific Integrated Circuits (ASICs) and bring GPS and LORAN receiver components onto a single card.

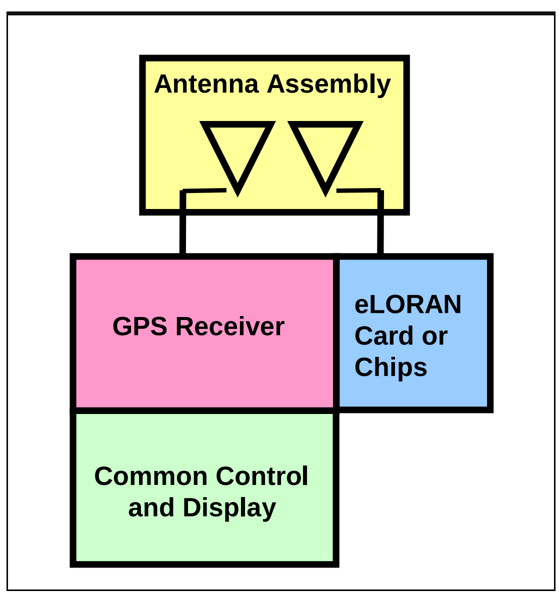

Figure 4-4: Common eLORAN and GPS Receiver

4.1.2.3 GNSS/INS[58]

For traditional navigation systems, the operational capability of the aircraft for a given procedure is linked to the availability of ground aids. A hybrid GNSS/INS system can provide improved navigation system capabilities when compared with traditional systems or with GNSS signals alone. The technical benefits derived from this hybrid depend upon the design architecture of the integration. Three types of integration: loose-coupling, tight-coupling, and ultra tight-coupling, have increasing degrees of complexity with increasing levels of benefit.

4.1.2.3.1 Loose-Coupling

Loose-coupling is the least complex with a position mixing of GNSS and INS. The technical benefit is position estimates with the high frequency characteristics of INS without the large time dependent biases. GNSS positioning accuracy aids in reducing the initial position and velocity errors[59] of the INS and improves coast time. The drift rates remain relatively large and little improvement in availability and continuity is gained in high performance air space with low RNP numbers. The gain in availability would be more significant in airspace with higher RNP values.

4.1.2.3.2 Tight Coupling

Tight-coupling adds complexity with the addition of more sophisticated filtering. Pseudo range measurements made by the GNSS receiver are combined with inertial measurements using Kalman Filters. The Kalman Filter estimates positions, velocity, and inertial error states (e.g. accelerometer biases, gyroscope misalignments, etc.)

A tight-coupled implementation improves availability through improved integrity monitoring. This gain is particularly beneficial for small RNP values where the current GPS system provides the least availability.

4.1.2.3.3 Ultra Tight Coupling

The ultra tight coupled system concept achieves the benefits of a tight-coupled system plus an effective 6-12 dB improvement in signal to noise ratio. The ability to operate in 6 – 12 dB higher noise environments, gives this architecture advantages in operating in areas where interference in the GNSS frequency spectrum is present.

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[58] This Section draws significantly from *Integration of GNSS and Inertial Navigation Systems*, International Coordination Council of Aerospace Industries Associations (ICCAIA), presentation paper to the Eleventh Air Navigation Conference, Montreal, 2003.

[59] Until Galileo becomes available, commercial loose coupling algorithms may be constrained to use standard INS coasting (e.g., not hybrid coasting) for RNP operations after GPS is lost. The reason for this is that there is a small probability that an undetected drifting satellite could miscalibrate a loosely-coupled GPS/INS hybrid, even if the GPS position is protected with RAIM. A miscalibrated solution could cause large coasting errors after GPS is lost, which jeopardizes RNP integrity. For this reason, present loose-coupling systems generally coast on INS velocity signals (or delta INS position) after GPS is lost. This coasting is suboptimal, especially after the airplane has flown several hours, because it is susceptible to INS velocity errors that

The complexity of ultra tight coupling presents technical challenges for implementation.

4.1.2.3.4 Coasting Capability

Table 4-6[60] presents estimates that compare the potential benefits of loose-coupled and tight-coupled GNSS/INS systems to provide availability and continuity improvements based on a Horizontal Protection Limit (HPL) with integrity of 10^{-7}.

Table 4-6: Loose and Tight Coupled System Performance

HPL Alert Limit *(Note: Not RNP value[61])*	Tightly Coupled		Loosely Coupled	
	Availability	Coasting Time	Availability	Coasting Time
4.0	100%	4 hours	RAIM/FDE	2 hours
2.0	100%	2 hours	RAIM/FDE	40 minutes
1.0	100%	20-40 minutes	RAIM/FDE	10 minutes
0.3	100%	10-18 minutes	RAIM/FDE	3 minutes
0.1	100%	7-12 minutes	RAIM/FDE	1 minute

A significant source of error in INS performance contributing to drift rate and consequently limited coast time is gravitational variation. For gravity compensation, coast time for tightly coupled systems could be extended beyond the values provided in Table 4-6.

4.1.2.3.5 Simulation Study of Inertial Capability in the Event of Terminal Area Disruption

Understanding coasting capability is an important element in assessing the ability of a GNSS/INS system. For assessing the capability of GNSS/INS to complete and also sustain operations, the scenario of a terminal disruption of SatNav capability was studied. This scenario would require aircraft to navigate from the en route domain to the terminal approach domain. A disruptive SatNav event with a radius of 40-60 nm centered at the destination airport was assumed. The requirement is that the aircraft would need to perform RNP-1.0 operations during terminal area STAR procedures. The need to navigate and support a RNP-0.3 NPA was further studied, while it was also understood

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develop during the flight. The addition of Galileo will solve this problem. Galileo and GPS could be cross-compared to detect a drifting satellite failure in either constellation.

[60] *Integration of GNSS and Inertial Navigation Systems*, International Coordination Council of Aerospace Industries Associations (ICCAIA), presentation paper to the Eleventh Air Navigation Conference, Montreal, 2003

[61] This note added by this SatNav Backup Study to the extracted Table from the cited reference. The value of Table 4-6 is to illustrate the improved benefits for coast time due with tightly coupled system from a loosely coupled system architecture. The relationship of "HPL Alert Limit" in the referenced report is assumed to be Horizontal Alert Limit. The final relationship to RNP requires additional assumptions about flight technical error and flight planning error. Values in this column should not be misinterpreted as RNP values.

that the RNP-1.0 terminal area operations could be sufficient in many cases to allow the aircraft to navigate to the intercept of an ILS to perform a precision approach.

In order to sustain operation, aircraft in the terminal area disruption region would also need to be able to perform terminal departure procedures to reach en route air space. For the GNSS/INS system, no GNSS fix would be available. It was assumed that satisfying terminal RNP-1.0 SIDs requirements should be sufficient for most airport regions.

Honeywell provided an essential aid to this study by conducting specific simulation studies to predict inertial system performance for each aspect of this scenario. Additional elements of the simulation study, presented in Appendix B.6, also helped to determine inertial system capabilities for surface operations. In addition[62], Honeywell projected cost, size, weight, and potential performance at the year 2015 that are of value to both the comparative cost analysis (Section 5) and this section.

With reference to Figure 3-11, the simulation study Defined Path overlays the Desired Path. Total System Error (TSE), Path Steering Error (PSE), and Position Estimation Error (PEE) are related as $TSE(t) = PSE(t) + PEE(t)$, where PSE and PEE are assumed to be independent random variables.

The Flight Technical Error (FTE) is a 10^{-5}/hr probability bound on PSE and is defined as FTE = 0.14 nm. The simulation analysis then determines the navigation system Containment Limit (CL) such that a 10^{-5}/hr probability bound on PEE is satisfied. The FTE and CL bounds assure the 10^{-5}/hr TSE and RNP integrity bound are satisfied. With multiple inertial components, the CL bound becomes the 10^{-7}/hr probability noted in the analysis. The simulation analysis is somewhat conservative as CL is a circular rather than lateral bound on INS error. This CL is the 'equivalent Horizontal Protection Limit (HPL)' noted in the following analysis summary Figures.

The simulation model assumed a tightly coupled system. The performances for a current inertial system and a projected High Accuracy Inertial Navigation System[63] (HAINS) were both predicted by the simulation study. The HAINS assumptions also included the incorporation of a gravity model. Figure 4-5 summarizes the system and modeling assumptions.

4.1.2.3.5.1 Coasting Performance During Approach

The assumed flight profile[64] for an approach and surface navigation is presented in Figure 4-6. The initial condition prior to 600 seconds assumes a tight coupling with GNSS. At 600 seconds, the GNSS is assumed lost. The resulting INS coasting capability bounded by the10^{-7} integrity limit is predicted with results graphed in Figure 4-7. A summary of the inertial coasting performance on

[62] Correspondence from Mark Manfred, Honeywell Engineering Fellow for Guidance and Navigation to Wayne Genter, ITT.

[63] The HAINS assumes gyro and accelerometer performances expected by 2015. It is important to note that today's export restrictions would not allow this level of performance for commercial INS.

approach is summarized in Figure 4-8. The results indicate that a tightly coupled INS could sustain RNP-1.0 operations for 37.5 minutes and RNP-0.3 operations for 18 minutes. The further performance prediction gains for the HAINS are significant.

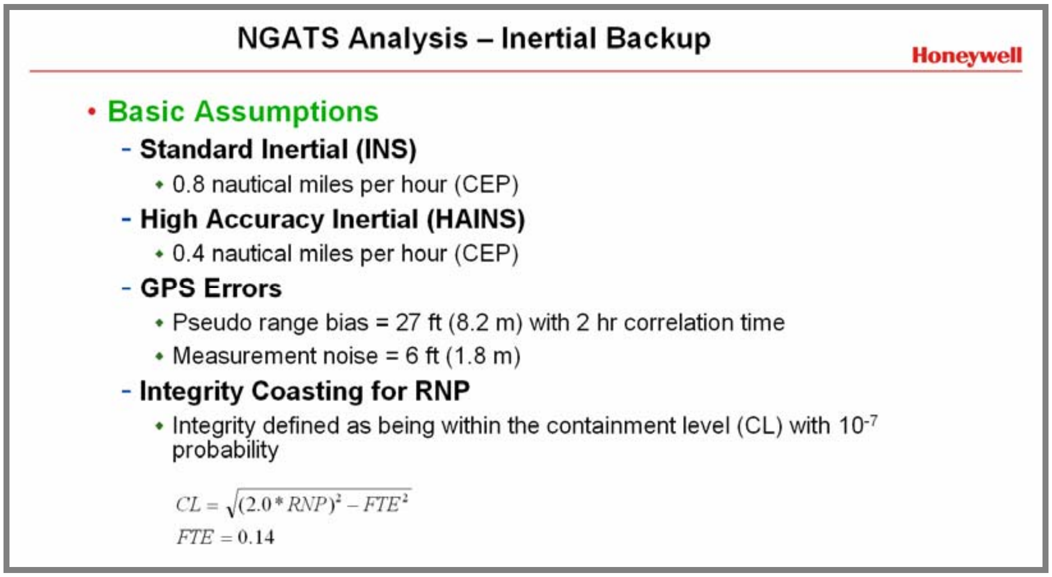

Figure 4-5: Simulation and Modeling Assumptions

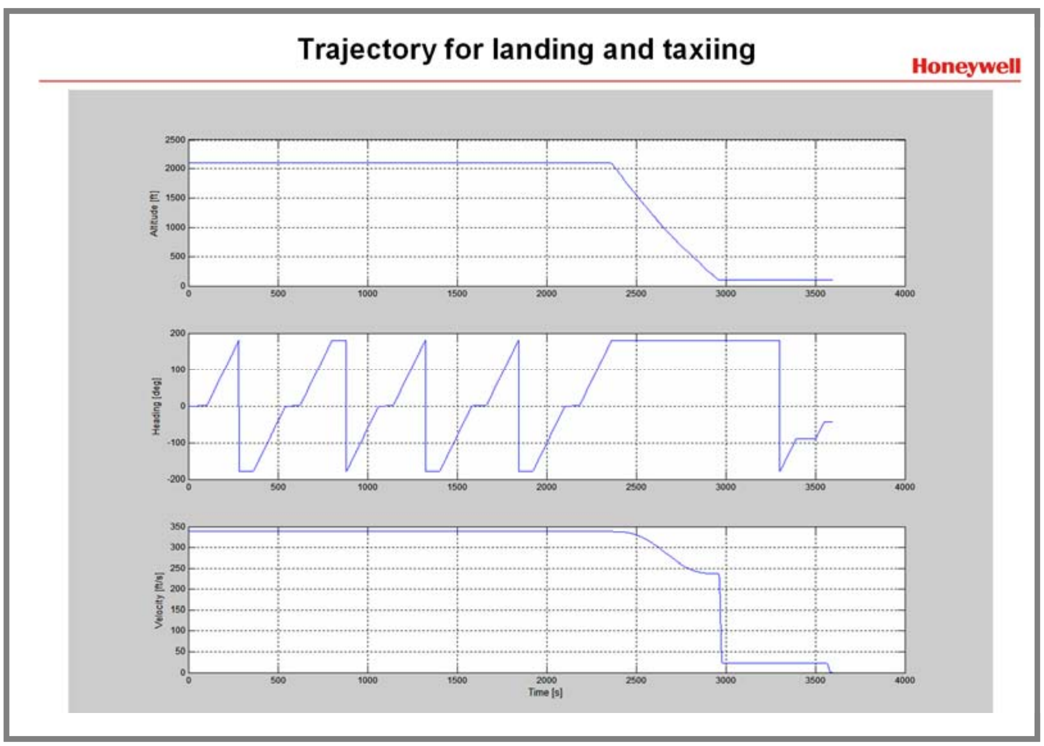

Figure 4-6: Assumed Profile for Approach and Surface Operations

[64] The trajectory includes three and a half circling paths after GNSS loss and prior to landing. This is considered a worst case scenario as compared with a straight in trajectory.

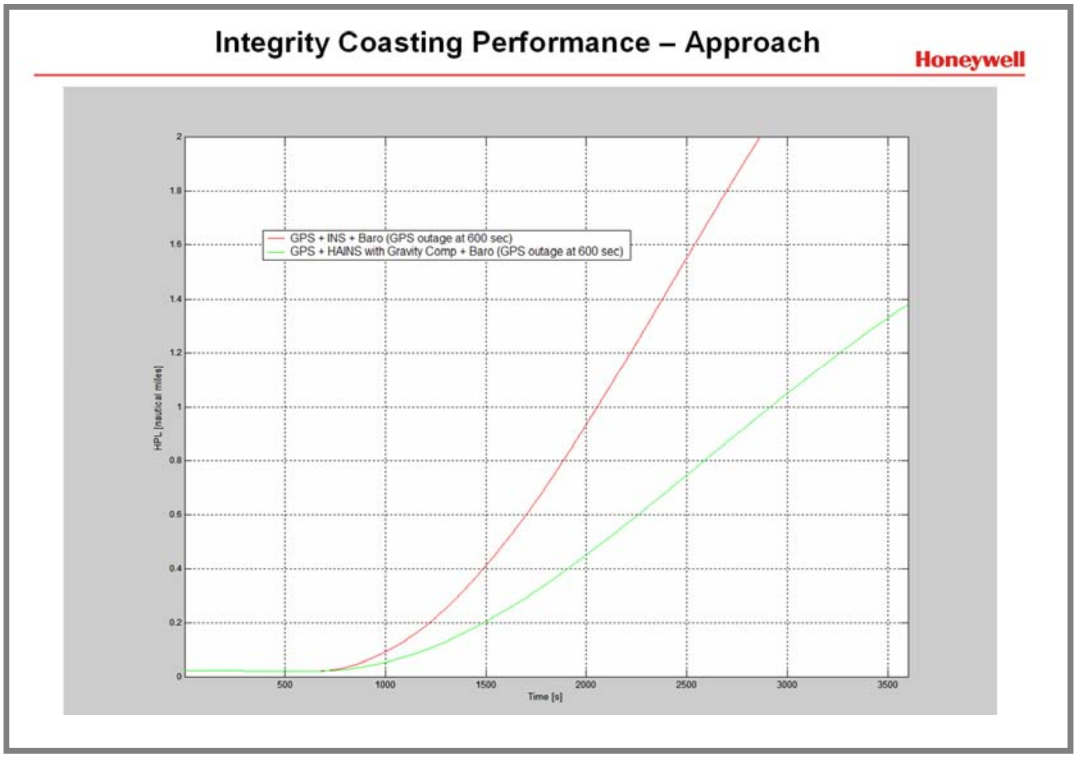

Figure 4-7: Predicted Coasting Performance

Integrity Coasting Performance – Approach

RNP (nautical miles)	Equivalent HPL (nautical miles)	Coasting time (minutes) for GPS/INS	Coasting time (minutes) for GPS/HAINS with Gravity Compensation#
0.1	0.143	8.75	12.25
0.3	0.583	18.0	27.0
1.0	1.995	37.5	>60.0

Gravity compensation is used in this analysis in conjunction with HAINS to predict coasting periods that can be achieved in the future. Systems of this accuracy may be subject to more stringent export restrictions than current INS for commercial aircraft.

Figure 4-8: Summary of Predicted INS and HAINS Coasting Performance

4.1.2.3.5.2 Coasting Performance for Takeoff

The terminal area disruption scenario also evaluated the capability of an aircraft to be able to perform takeoff and terminal departure procedures in the absence of SatNav. The benefits of any prior tight coupling to improve calibration were not applicable to this takeoff and departure case.

The results for integrity coasting following the ground update are graphed in Figure 4-9 and summarized in Figure 4-10. Assuming placement of a position update beacon or appropriate sensor at the runway, this simulation study predicted that RNP-0.3 procedures could be maintained for 10.5 minutes and RNP-1.0 procedures for 18.5 minutes. The HAINS system was predicted to be capable of maintaining RNP-1.0 operations for 25 minutes.

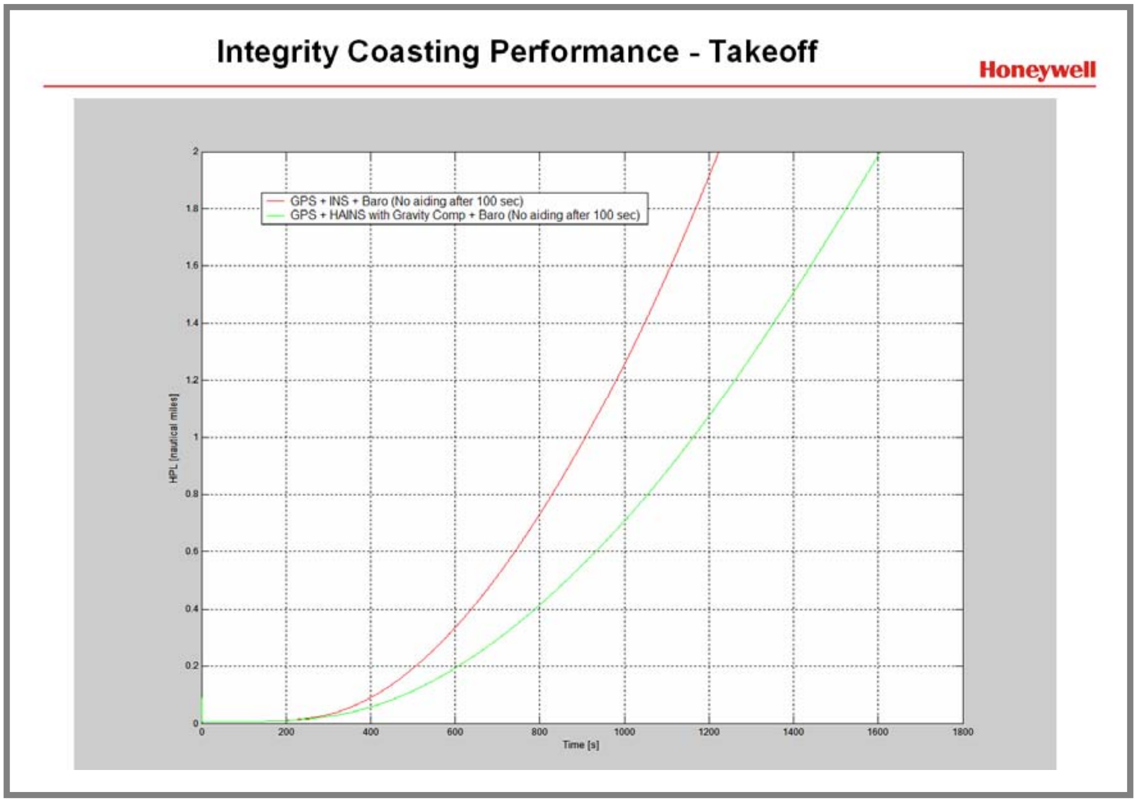

Figure 4-9: Summary of Predicted INS and HAINS Coasting Performance for Takeoff Following a Ground Position Update

Integrity Coasting Performance - Takeoff

Honeywell

RNP (nautical miles)	Equivalent HPL (nautical miles)	Coasting time (minutes) for GPS/INS^	Coasting time (minutes) for GPS/HAINS with Gravity Compensation^
0.1	0.143	6.0	7.25
0.3	0.583	10.5	13.5
1.0	1.995	18.5	25.0

^ This analysis assumes an accurate position update while the aircraft is at the terminal before taxiing for takeoff

^ Since the aircraft is not moving during the position update there is no Calibration of the inertial system and the coasting times are much smaller compared to the "approach" case

Figure 4-10: Summary of Predicted Coasting for Taxiing for Takeoff Following a Ground Position Update

4.1.2.3.6 GNSS/INS Area Navigation Conclusions

The performance of standard INS and HAINS in satisfying the team requirement for a terminal area disruption is summarized in Table 4-7. For a disruption radius of 40-60 miles, the standard INS was capable of supporting STAR RNP-1.0 requirements to the approach. For a direct approach without added holding delay, the standard INS was determined to be conditionally capable of supporting navigation to a RNP-0.3 NPA. This SatNav backup study does not address operations requiring RNP-0.1 performance[65].

To sustain operations, aircraft must also be able to take off and depart from an area of SatNav disruption. The assumption in this scenario is an accurate runway position reference for the INS at takeoff. The standard INS will sustain RNP-1.0 for 18.5 minutes, sufficient to perform terminal SID procedures and exit the assumed disruption radius. For SID procedures requiring RNP-0.3, the standard INS could sustain navigation performance for 10.5 minutes. For SID procedures requiring this RNP level, the standard INS performance was determined to be marginal to navigate the necessary 40-60 nm.

The HAINS assumptions provided extended coast times for both the arrival and departure case. With the 40-60 mile disruption radius assumption in this scenario, and with conditional assumptions such as direct approach operations without added hold time, the advantages of improved INS

[65] It is expected that this performance requirement may be needed for obstacle avoidance or for horizontal navigation guidance to tightly spaced parallel runways.

performance are not pronounced. However, if the assumption of disruption radius was 60-100 miles, the HAINS assumptions would provide clearly superior performance to the standard INS.

Table 4-7: Summary of Performance of GNSS/INS System in Terminal Area Operations as SatNav Backup

Performance Requirement following GNSS disruption	Standard INS	High Accuracy INS with gravity compensation
Sustain RNP 1.0 from en route through terminal area to the approach	Capable (37.5 minutes)	Capable (>60 minutes)
Sustain operations from en route through terminal area to perform RNP-0.3 NPA	Conditionally Capable (with direct approach without hold) (18 minutes)	Capable (27 minutes)
Take off and departure maintaining RNP-1.0	Capable (18 minutes)	Capable (25 minutes)
Take off and departure maintaining RNP-0.3	Marginal (10.5 minutes)	Marginal (13.5 minutes) (additional ~ 10-15 nm.)

4.1.2.4 VOR

The Very High Frequency (VHF) Omidirectional Range (VOR) system is a common navigation aid. VOR ground systems transmit a modulated signal that provides the azimuth angle to the aircraft from to the transmitter location. The pilot will know the location of the VOR station, and with the azimuth information the aircraft bearing from the ground location is determined. Aircraft have traditionally flown from ground reference to ground reference with a flight path consisting of radial lines from one VOR transmitter to the next. The pilot would over fly the VOR systems along the flight path.

If two VOR systems are in view and with acceptable geometry, the aircraft can determine its position from the azimuth determinations relative to the ground transmitter locations. It is common that VOR and DME transmitters are collocated. With this combined system, the aircraft derives its azimuth and distance relative to the ground station. Modern VOR avionics enable RNAV operations by electronically deriving position and presenting cockpit displays relative to desired flight path, closely similar to a radial line fix to or from a VOR station. VOR remains a common equipage in most aviation segments.

Since VOR systems are line of sight transmission, service coverage for low altitude aircraft would require a considerable investment in ground stations. VOR ground locations also require a clear zone around the antenna structure that is free of blocking or reflective obstructions. A significant limitation of the VOR systems is the maximum receiver uncertainty of ±6° in determining azimuth, resulting in possibly large position uncertainty. If the two VOR stations are not geometrically close to 90° in separation from the aircraft, the uncertainty of position grows rapidly. Additional VOR systems to support future RNAV and RNP requirements for aircraft at all elevations would be

technically difficult and costly. The U.S. and Europe both plan to reduce the number of VOR stations significantly by 2015[66] [67].

A retained VOR network is not regarded as a viable solution for supporting continuing routine operations in the event of a SatNav disruption[68]. In this event, aircraft navigating with VOR ground aids might not be able to navigate to and land at their planned destination. A minimum VOR network is to be maintained through the near term (2015) that will provide necessary navigation support for the recovery of aircraft caught in an interference event. In addition to providing en route guidance, an objective of the minimum VOR network is to provide landing aids at airports, either for a non precision approach (not RNP-0.3) or for guidance to an ILS.

Policy decisions will continue to evaluate the retention of the VOR system beyond 2015.

4.1.2.5 'Hardened' GNSS Receiver

This candidate is not a true SatNav *backup* in that it is not independent of GNSS[69]. This candidate rather was considered in that it aided in the mitigation of the primary threat of denying GNSS service by intentional or unintentional interference sources. The benefit is that it would provide the capabilities of SatNav to all phases of flight operation while addressing the directives of *December 17, 2003 Homeland Security Presidential Directive/HSPD-7.* This candidate does not satisfy the *U.S Space-Based Positioning, Navigation, and Timing Policy, December 15, 2004,* however, that calls for <u>backup</u> navigation capabilities to support critical transportation navigation systems. Since this candidate did not satisfy the Policy directive, it could not pass the candidate screening process (described in Section 4.3).

Elements of this concept are:

- Gain steering or nulling antenna with supporting signal processing to discriminate against single or multiple interference sources,
- GNSS RAIM receiver with full GPS and Galileo constellations, with fault detection and isolation, and
- Ultra-tight coupling of the GNSS receiver and an IRU (low cost) for 6-12 dB improved signal acquisition.

The low cost inertial reference unit with high drift rate adds negligible coast time so the system would be unable to track GNSS for more than a few tens of seconds, and thus would not be a *true*

[66] 2005 *Federal Radio Navigation Plan*
[67] Helios technology, *System and Policy Inventory, Development of the European Navigation Plan, 2004*
[68] *Navigation and Landing Transition Strategy*, FAA, 2002
[69] A "backup" system is considered to be one that can operate during the disruption of the primary system. Thus the GNSS/INS candidate can be considered a backup because its navigation grade INS allows it to continue to operate for sufficient periods of time in the absence of GPS signals, while the hardened GNSS system, with a less capable inertial reference unit, once disrupted, would only operate for a few seconds until the disruption ceased.

SatNav backup. If this low cost IRU was replaced with a higher quality navigation grade INS system, then this solution would become a high cost and complexity version of the GNSS/INS solution described in Section 4.1.2.3.

The concept goal was to take advantage of the higher acquisition gain to improve GNSS acquisition and tracking, thereby reducing the radius of GNSS denial from an interference source. If the radius could be reduced sufficiently, an opposite end approach to a runway, or the opportunity to use nearby airfields would provide some mitigation.

4.1.2.6 Terrain Reference Navigation

Terrain reference navigation (TRN) systems estimate the user position based on a best match between measured surface features and a terrain database. Airborne measurement methods include radar and laser ranging systems. The application of TRN systems is to help bound the error growth of inertial systems while coasting. As yet TRN system implementations have been primarily limited to military applications.

The application of TRN to civil aviation could provide an autonomous navigation capability in the sense that it would be independent of external navigation aids after initialization. TRN has the potential for application to area navigation and for providing horizontal guidance for precision approaches.

A "proof of concept[70]" system has demonstrated the ability to bound inertial error growth to meter level accuracy. In addition to the inertial component, this system requires:

- A high resolution, high accuracy surface data base of the surface contours and features
- A laser ranger
- A laser scanning mechanism
- Computational hardware to store and process data
- Algorithms to determine correlation and best fit of measured contours with the reference data base

The objective of the collective TRN system is to determine a unique position for the aircraft.

The necessary high resolution, high accuracy surface contour data base can be created by a LIDAR (Light Detection and Ranging) system. A LIDAR mapping system is capable of generating dense

[70] *Application of Airborne Laser Scanner – Aerial Navigation*, 2006, PhD Dissertation, Russ College of Engineering and Technology of Ohio University, Jacob L. Campbell contains a good survey of TRN technology history, applications, and component trade-off issues. It presents a 'proof of concept' for bounding inertial growth errors to support the final segment of a CAT I approach from the decision height enabled by GPS/WAAS.

(1 meter spacing) and accurate (decimeter level horizontal and vertical position) data. A laser ranger and scanner is also an element for airborne LIDAR mapping systems.

The algorithms to determine the best estimate of position can be computationally intensive. If a reasonable position estimate is not known *a priori*, an exhaustive search over a broad area becomes extremely computation/time intensive and may not resolve a unique position. The intended application for TRN is to assist an inertial system in helping to bound error growth during periods of coasting. In this application, with an assumed correct *a priori* position, the numerical search can be significantly limited and the risks for multiple position solutions reduced. With an accurate initial calibration of the INS to GPS, the "proof of concept" system was able to maintain position navigation with real time computation over the final precision approach phase of flight tests.

The military has made prevalent application of radar altimeter based terrain navigation systems. Radar is a better all weather solution with some loss in sensor resolution as compared with laser. The resulting resolution however seems adequate from reported performance results for most aircraft operations. Horizontal accuracies of 3 meters at altitudes below 5000 feet and 30 meters at altitudes below 30,000 feet have been achieved for a system called PTAN[71]. One benefit of a TRN system is that its accuracy improves as the airplane descends in altitude, which is where accuracy is most important (approach and departure).

An identified benefit of TRN for civil aviation is that it can work in undeveloped countries that have limited infrastructure of radio navigation aids. Another application benefit can be seen from a scenario where an aircraft looses GNSS in oceanic flight. Here the aircraft would fall back to INS for navigation until it reaches the coastline. In this scenario, PTAN demonstrated that it could provide a navigation fix about 30 seconds after the airplane reached the coastline.

TRN systems are not applicable for navigation over the ocean or flat featureless terrain. Landscape with repetitive features such as a grid of residential housing or warehouses with similar construction could also need special consideration.

Laser or radar based TRN is a promising technology that could extend the coast time for a GNSS/INS system for supporting area navigation if GNSS was unavailable, and in theory could be a near autonomous navigation system. This concept has application as a SatNav backup for aircraft for area navigation and the potential for precision approaches. However, establishing the accuracy and integrity of the terrain data base may pose a significant challenge.

The study team could not adequately assess the technical maturity readiness of the TRN technology. The TRN concept will require additional research and development, particularly to demonstrate

[71] Honeywell Precision Terrain Aided Navigation (PTAN) summary found in Jacob L. Campbell citation.

necessary integrity performance and for availability and continuity in all weather conditions. In this study, the TRN system did not clear the initial candidate screening due to:

- Technical maturity readiness evaluation and the requirement that the candidate be available for civil aviation equipage in 2015-2025
- The expected significant TRN cost increase to the base GNSS/INS system
- The anticipated difficulty in retrofitting this technology into existing aircraft
- The understanding that terrestrial navigation systems are subject to export restrictions that could limit the application of this technology to civil aviation

4.1.2.7 Multilateration

This concept features aircraft periodically transmitting position or identification signals that would be received at several ground locations, where the ground receivers and an element for coordination and processing would determine aircraft position by the Time Distance of Arrival (TDOA) principle.

Multilateration can be active or passive. An active system is illustrated in Figure 4-11, where the system transmits SSR or SSR-Mode S interrogations to trigger a transponder reply or to request additional Mode-S data.

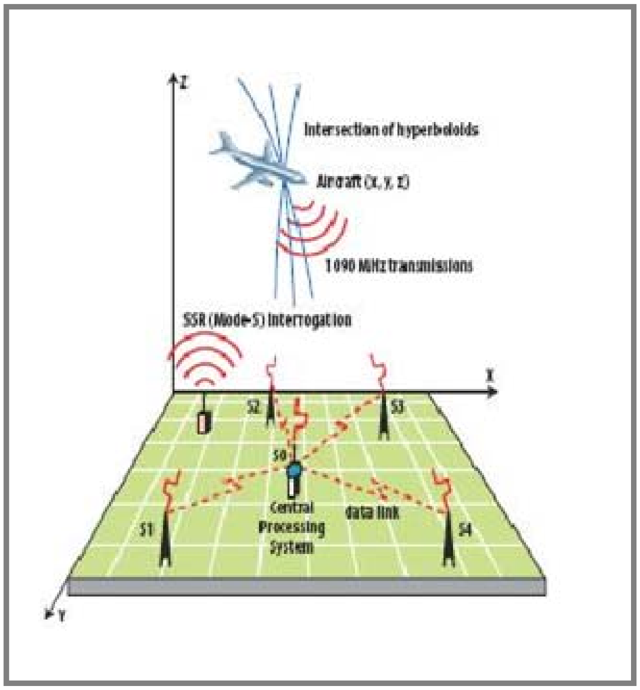

Figure 4-11[72]: Active Multilateration System Example

The Time Distance of Arrival between the receiving antennas allows the central processing element to compute the intersection of hyperboloids from the respective known ground receiving antenna

[72] From http://www.eurocontrol.int/surveillance/public/standard_page/sur_WAMevent.html; announcement webpage for EUROCONTROL organized WAM Workshop, June 4-5, 2007.

locations. With four receiving stations, a multilateration system is able to compute a 3-D position determination (reference Figure 4-12).

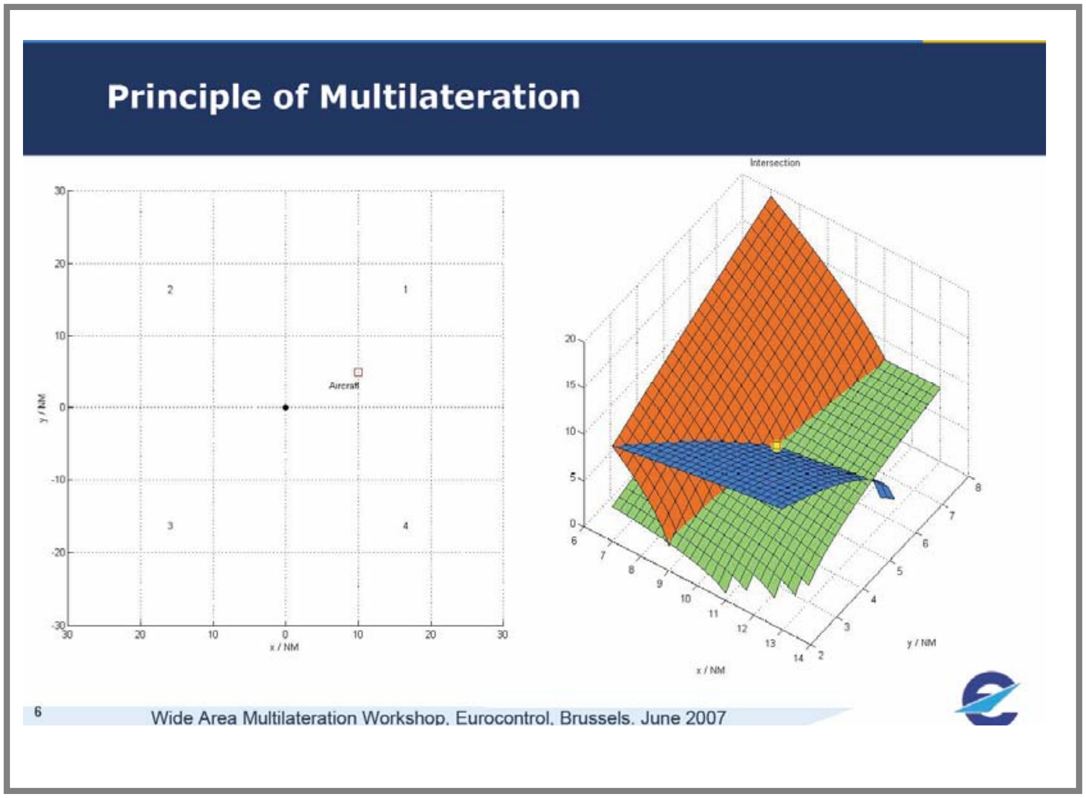

Figure 4-12: Principle of Multilateration and Intersecting Hyperboloids[73]

Multilateration is a proposed element in certain surveillance architectures. Where such systems cover a larger air space for en route or terminal approach, the concept is called Wide Area Multilateration (WAM).

Application challenges for the multilateration concept include[74]:

- Problems of interference in high traffic density areas
- Variable update rate dependent on radar type
- Traffic density may limit useful range
- Low bandwidth of the signal makes TDOA accuracy poor

For surveillance functions, a vendor[75] indicates that in areas with sufficient ground station coverage, aircraft positions could be determined by multilateration with sufficient accuracy and reliability to

[73] *WAM Workshop Agenda Item 3 Multilateration Principles*; Wide Area Multilateration Workshop, Eurocontrol, Brussels. June 2007

[74] Ibid. Slide #6.

[75] SENSIS Press Release, February 13, 2007; *Canada to Deploy Sensis ADS-B and Wide Area Multilateration Surveillance*.

assure 5 nm lateral separation. The ability of multilateration to determine aircraft position has generated some questions about its suitability to provide navigation guidance.

4.2 IDENTIFICATION OF THRESHOLD CRITERIA FOR SCREENING

In Section 3, performance requirements and desired capabilities are identified and organized into evaluation decision factors for an Area Navigation SatNav backup system. In the defined Analytical Hierarchy Process (AHP) approach for assessment of backup solutions, a subset of the criteria that define a threshold of applicability are identified and used to screen alternatives to identify viable candidates for further considerations. To select appropriate threshold criteria, criteria were grouped into three applicability categories as follows:

- Essential (Level 1)
- Strongly preferred (Level 2)
- Preferred (level 3)

All evaluation criteria associated with technical requirements were assigned to the Essential applicability category. The remaining criteria were assigned based on the functional/operational context and needs for a backup solution as well as on initial preference/importance of criteria inferred from the first round of stakeholder interviews. The result of this evaluation criteria organization is shown in Table 4-8.

Table 4-8: Ordering of Evaluation Criteria

Technical Requirements and Desired Capabilities		Criteria Level
Technical Requirements	≤ RNP-2.0 en route	(1)
	≤ RNP-1.0 terminal	(1)
	RNP-0.3 NPA	(1)
Functional Requirements and Capabilities	Technical readiness in 2015-2025	(1)
	Backup system must be independent and not reliant on GNSS.	(1)
	Redundant capability and minimal operational impact	(2)
	Long term flexibility	(3)
	Low life cycle cost (desired characteristic)	(2)
	Global harmonization (goal)	(3)
	Early Avionics Availability	(3)
	Spectral Efficiency	(3)
	Additional Key Infrastructure Protection	(3)

In the table above, the evaluation factors identified as essential (Level 1 criterion) were considered to be threshold/screening criteria for evaluation of candidate solutions.

The ≤ RNP-2.0 en route and ≤ RNP-1.0 terminal area requirements align with the projected minimum navigation performance requirements for performing operations in managed airspace. The RNP-0.3 requirement aligns with the navigation performance necessary to perform a non precision approach, a common runway approach procedure performed in instrument meteorological conditions.

The requirement for technical readiness in 2015-2025 is derived from the Study Objective, that is, to identify candidate solutions at 2015, 2020, and 2025.

The requirement that the backup must be independent and not reliant on GNSS allows the navigation system to continue to provide necessary guidance in the event of a disruption to GNSS and is based on National Policy to provide such backups.

The threshold/screening criteria were applied in the alternatives screening process (in the following subsections). The remaining evaluation decision factors will be applied in a later part of the analysis (see Section 6).

4.3 SCREENING ALTERNATIVES TO IDENTIFY APPLICABLE BACKUP CANDIDATES

4.3.1 Screening Process

The identification of SatNav backup solutions for further consideration requires the determination of the ability of each identified backup candidate to satisfy the defined threshold criteria. This constituted the candidate screening process.

A summary of the screening of candidates to threshold criteria is provided in Table 4-9

Candidates GNSS/INS and eLORAN were determined to satisfy all the essential screening criteria. DME/DME/INS passed the screening criteria with the team opinion that it would “maybe” be capable of supporting RNP-0.3 navigation performance requirements. The candidate passed the screening with the understanding that with proper ground sighting of DME stations and with FMS avionics to operate with all-in-view technology (not just a single pair wise position determination), this performance could be achieved where required.

Table 4-9: Screening SatNav Backup Alternatives (Applying Threshold Criteria)

Alternatives		Threshold Criteria				
		≤ RNP-2.0 en route	≤ RNP-1.0 terminal	RNP-0.3 NPA	Technical readiness in 2015-2025	Backup system must be independent and not reliant on GNSS
DME/DME	Assessment	Meets	Meets	Maybe	Meets	Meets
eLORAN	Assessment	Meets	Meets	Meets	Meets	Meets
GNSS/INS	Assessment	Meets	Meets	Meets	Meets	Meets
VOR	Assessment	Meets	Difficult	Doubtful	Meets	Meets
Hardened GNSS	Assessment	Meets	Meets	Meets	Policy	No
Terrain Ref	Assessment	Potential	Potential	Potential	Doubtful/ Policy	Meets
Multi-lat	Assessment	Potential	Potential	Potential	Potential	Meets

VOR would require a significant network expansion, rather than the reduction it is experiencing, for it to provide support for performance based navigation. The user costs are low because VOR is common equipage. However, infrastructure costs would be high. The application of the VOR system to meet the requirements of RNAV and RNP air space operations is neither technically or economically feasible. The Study Team determined that VOR did not pass the threshold screening process due to the high infrastructure cost and technical issues for support of high performance airspace.

There was consensus in the team that the Terrain Reference Navigation system technology has a low technical readiness level that precludes civil navigation systems within the 2015-2025 time frames. The system also adds an assumed high cost and complexity to inertial systems.

The hardened GNSS system fails this screening primarily because it does not provide an independent sustainable backup of GNSS. On the other hand, it is the only candidate that can closely equal the performance of the primary GNSS navigation system in all phases of flight operation. Policy issues on transferring these sensitive technologies from military to civil applications could also be an obstacle.

Multilateration is a concept that might potentially satisfy the technical requirements but at a very high cost for users and providers. Accuracy requirements could likely be satisfied for the technical screening criteria. The ability of this concept to satisfy integrity and availability requirements were not understood. Data links would be required to provide real time position updates to the aircraft and its integration into an FMS would be necessary if the concept could prove to satisfy the technical

requirements. Multilateration system concept costs were difficult to estimate, other than that they would be very high[76]. This concept was determined to provide no significant benefit compared with better cost effective area navigation candidates. Unless this strategy was employed in other systems such as surveillance, the system complexity and cost are not justifiable solely from the navigation perspective. The Surveillance Backup Analysis Team has recommended SSR as a backup for surveillance systems, so plans to implement a national wide area multilateration system do not seem to exist. Multilateration did not pass the threshold screening process as a first level candidate.

Based on the results of the screening process, two tiers of backup alternatives were defined. Those in Tier 1 meet the threshold criteria and were considered further with respect to the full set of evaluation criteria. Those identified as Tier 2 are less suitable candidates, as they fail to fully meet all the threshold criteria. Table 4-10 summarizes this organization of alternatives.

Table 4-10: Area Navigation Alternatives Screening

Area Navigation SatNav Alternatives	Applicability Level
DME/DME/INS	**Tier 1**
eLORAN	**Tier 1**
GNSS / Inertial	**Tier 1**
VOR Minimum Operational Network	**Tier 2**
Hardened GNSS receiver	**Tier 2**
Terrain Reference Navigation	**Tier 2**
Multilateration	**Tier 2**

Based on the results noted in the table above, three alternatives emerged for further consideration as candidate alternatives for a SatNav backup solution. These included DME/DME/INS; eLORAN and GPS/Inertial. These candidates were considered further against the remaining set of evaluation criteria (see Sections 5 and 6). Note, that although VOR is a Tier 2 candidate, it may have a secondary role in providing navigation guidance in non managed air space at least through 2015. This role is likely due to current ground aids and common VOR equipage by general aviation.

4.3.2 Additional Information for Considered Candidate Solutions

As input to the assessment to further consider the three identified candidate solutions, a set of strengths and weaknesses associated with each of the candidates has been identified. This information is captured in the following subsections.

[76] Costs for active and passive multilateration systems as backup positional sources for ADS-B are presented in the Surveillance/Positioning backup study. Because these costs estimates were developed to meet surveillance system backup requirements, their applicability to a navigation system backup solution is not readily discernible.

4.3.2.1 DME/DME/INS Strengths/Weaknesses

4.3.2.1.1 DME/DME/INS Strengths

- Capable of sustaining operations over an extended period
- Common equipage of Air Carriers
- DME infrastructure supports most of RNAV 2.0 en route air space.
- DME infrastructure supports most of RNAV and RNP 1.0 terminal SIDs and STARs procedures.
- Can provide continuous SatNav backup in areas of DME coverage
- INS component can continue to support navigation in the event of SatNav loss and the aircraft is between areas of DME/DME coverage.
- INS provides navigation in oceanic regions beyond the range of radio navigation aids.
- Inertial systems will benefit from reduced cost, size, and weight (2015)

4.3.2.1.2 DME/DME/INS Weaknesses

- Considerable additional infrastructure modifications and expansion may be required for higher performance levels from the RNAV-2.0 en route and RNP-1.0 terminal requirements.
- Considerable additional infrastructure modifications and expansion may be required to support RNP-0.3 non precision approaches.
- DME/DME sighting for RNP-0.3 non precision approaches may be difficult to achieve.
- In order to achieve RNP-0.3, this may require FMS systems to use all-in-view DME solutions.
- DME is a high consumer of aeronautical spectrum.
- DME/DME does not provide for accurate calibration of the INS. For equivalent grade INS, DME/DME/INS cannot achieve the coast time characteristics of GNSS/INS.
- The inertial component makes this system expensive for many users.

4.3.2.2 eLORAN Strengths/Weaknesses

4.3.2.2.1 eLORAN Strengths

- Capable of sustaining operations over an extended period
- Uses a similar all-in-view concept as with GNSS to derive position from all available transmitters in range
- Seamless and redundant to SatNav, for area navigation flight operations

- Can support RNP-0.3 NPA at all airports in CONUS and Alaska without additional infrastructure
- Flexible and scalable. Can accommodate changing performance requirements for an air space down to RNP-0.3 without expansion of infrastructure beyond the capitalization plan
- Low frequency signal propagations are not limited to line of sight and not easily impeded
- Low frequency signal and high power allow reception 1000+ miles from transmitters
- Denial of eLORAN signals by a local jammer would be difficult.
- Non consumer of aeronautical frequency spectrum.
- With completion of eLORAN modernization and expansion, coverage of CONUS and Alaska would be good.
- Good repeatable accuracy. With conductivity path correction factors, absolute position accuracy is about 20 m.
- eLORAN could also serve as GNSS backup to many other PNT users.

4.3.2.2.2 eLORAN Weaknesses

- No current eLORAN avionics equipage. Current avionics equipage is LORAN-C and cannot take advantage of eLORAN enhancements.
- Equipage would require antenna assembly. This would only be a significant issue on retrofits.
- eLORAN is not presently considered as an international or global air navigation strategy. Government policies, both in the U.S. and in other countries with LORAN type systems have not affirmed long term LORAN support. Policy decisions for continued funding or decommissioning are pending for all.
- LORAN systems and coverage do not presently exist in Hawaii, Latin and South America, Australia, and Africa. Coverage in Europe would need expansion. Coverage in Asia is spotty.
- For better global harmonization, U.S. and other operators of LORAN would need to agree on interoperability and similar modernization and operating strategies as eLORAN.
- eLORAN may need correction factors annually, seasonally, or more often to allow navigation to meet the requirements of NPA. The need for a single correction factor or a grid of factors across a terminal area is not yet understood. Research studies are incomplete. If repetitive surveys or a more granular grid of factors are needed, this would add to O&M costs and also make eLORAN avionics more complicated.
- A body of national and international standards would need to be developed for U.S. and international aviation acceptance of eLORAN.
- FAA would need to make a policy issue for aircraft to depend on a non aeronautical band frequency.

- Does not provide navigation in oceanic regions outside range of eLORAN transmitters.

4.3.2.3 GNSS/INS Strengths/Weaknesses

4.3.2.3.1 GNSS/INS Strengths

- In the event of GNSS loss, the inertial supports a seamless failover to the backup for navigation capability
- The inertial and GNSS are complementary systems with synergistic characteristics that allow improved navigation capability and extended inertial coast time (compared with DME/DME/INS).
- Inertial systems will benefit from reduced cost, size, and weight (2015).
- Gyro and accelerometer technical improvements (2015) with the addition of gravity compensation could significantly add to the coast time. Extended coast time translates into larger radii of an interference event that can be mitigated with this solution.
- If ultra tight coupling concepts can be achieved with low cost inertial units in the future, this will provide additional signal to noise ratio capability and decrease sensitivity to interference.
- If tight/ultra tight coupling concepts can be achieved with low cost inertial units, this would reduce costs.
- A tightly coupled system would enable the INS to sustain RNP-1.0 for a sufficient coast time through a terminal area disruption to the approach.
- Given new concepts on ground point INS updating, this candidate could further support surface navigation requirements.
- Given new concepts in ground point INS update, this candidate could support RNP-1.0 departures in the absence of GNSS.
- Hybrid coasting provides backup navigation if GNSS is lost in oceanic regions.

4.3.2.3.2 GNSS/INS Weaknesses

- The inertial component makes this system expensive for many users.
- If GNSS is disrupted, the system relies only on the inertial system to provide a coast time. For a wide area or total system disruption, this system could not sustain operations. This weakness makes it not as robust a solution for sustaining operations as other candidates.
- The 18 minute coast time (for tightly coupled systems) to perform a RNP-0.3 NPA is considered only conditionally acceptable in the event of a terminal area disruption. This assumption is insufficient if the approach is not direct or if holding time is required.
- The application of high accuracy INS (HAINS) may be restricted from application to civil aircraft by export control policy.

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5. COST CONSIDERATIONS

5.1 COST ASSESSMENT INTRODUCTION

One objective of the SatNav Backup Study was to evaluate potential solutions to aid in the formulation of the NextGen concept of operation and architecture. As one of the NextGen objectives is to "reduce the cost of aviation"[77], understanding the relative cost of proposed backup solutions is important. Additionally, cost has been specifically identified by stakeholders as a factor to consider when evaluating backup solutions, and it has been included as a decision factor in the applied evaluation process in this study. The material in this section provides a detailed view of the cost assessment performed, considering the cost impact of each proposed solution to both provider and user stakeholders.

To perform a cost comparison of the proposed SatNav backup solutions, a methodical cost analysis approach was applied. This approach, derived from cost estimating methodology defined in the NASA Cost Estimating Handbook[78], is shown in Figure 5-1.

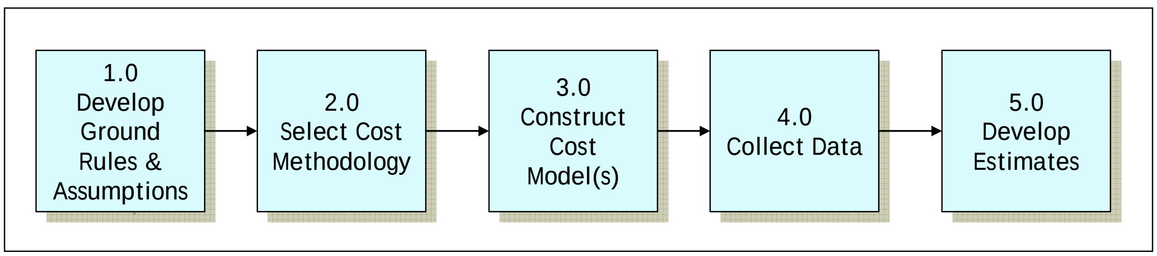

Figure 5-1: Comparative Cost Assessment Approach

The figure above outlines a five step process applied for cost assessment. The first step is to communicate the context in which the assessment is being made. Then, Step 2 is the selection of the best cost methodology to be applied based on available data. The third step includes the selection of the tool and creation of the cost model to perform the cost assessment. Then, to apply the developed cost model, a fourth step is to gather data to support the development of cost estimates. And, finally, Step 5 is the application of the model using the gathered data to generate cost estimates. Details of the work specific to these applied cost assessment steps are provided in the following subsections.

5.1.1 Develop Ground Rules and Assumptions

Cost estimation in the aeronautical environment can be complex. There are a range of stakeholders with varying contributions and implemented aeronautical system elements. Additionally, within common stakeholder sets, there may be few to many hundreds of specific configurations of current

[77] *Concept of Operations for the Next Generation Air Transportation System*, version 1.2, Joint Planning and Development Office, February 28, 2007, Table 1-1.
[78] *NASA Cost Estimating Handbook*, National Aeronautics and Space Administration, 2004.

system implementations and capabilities. Therefore, to perform a cost assessment specific to the proposed candidate SatNav backup systems, certain ground rules and assumptions must be defined.

Three ground rules were defined for this study. Specifically:

- GR-1: Cost estimates are based on stakeholder cost drivers
- GR-2: Cost assessment results identify cost distributions among system participants
- GR-3: The cost assessment focus is the relative costs of the proposed solutions

The first ground rule limited cost evaluation to those items which were identified to have the most significant impact on stakeholder costs. The objective of this study was not to develop a cost estimate for implementing a SatNav backup solution, but rather to provide a comparison of the proposed solution candidates. The second ground rule indicates that the cost of the proposed solution should be evaluated from both a service provider and user perspective, to gain an understanding of the cost distribution among all system participants. And finally, the focus of the cost assessment was to understand the relative differences between costs associated with each solution rather than to estimate total costs associated with implementation of a specific solution.

To apply these ground rules, an organization of the applicable stakeholders from the cost perspective needed to be defined. It was clear that the stakeholders included ground navigation service providers; related transportation system operators (maritime); and airspace system users (air carrier-commercial, air carrier-regional, air carrier-air taxi, air transport, and general aviation). The organization of service provider/operator stakeholders applied was specific to the types of systems operated. For airspace users, an organization based on service (passenger/cargo/personal) and aircraft type was assumed to be most applicable as user-related costs (equipment, installation, certification etc) may vary significantly among these divisions. For the cost assessment of this study, the applied organization of stakeholders is documented in Table 5-1.

Table 5-1: Cost Assessment Stakeholders

High-Level Category	Cost Assessment Stakeholder
Ground System/Service Operator	Air Navigation Service Provider (ANSP)
	Maritime System Operator
Navigation System User	Air Carrier- Jet
	General Aviation – Jet/Turbo Prop
	General Aviation – Piston/Rotorcraft

The next step in the application of Ground Rule -1 (GR-1) was to define the cost drivers applicable to the defined set of stakeholders. At a high level, cost across a system life cycle was organized into four major categories. These included research and development; investment; operations and maintenance and termination. A depiction of these costs in the context of a system implementation is shown in Figure 5-2.

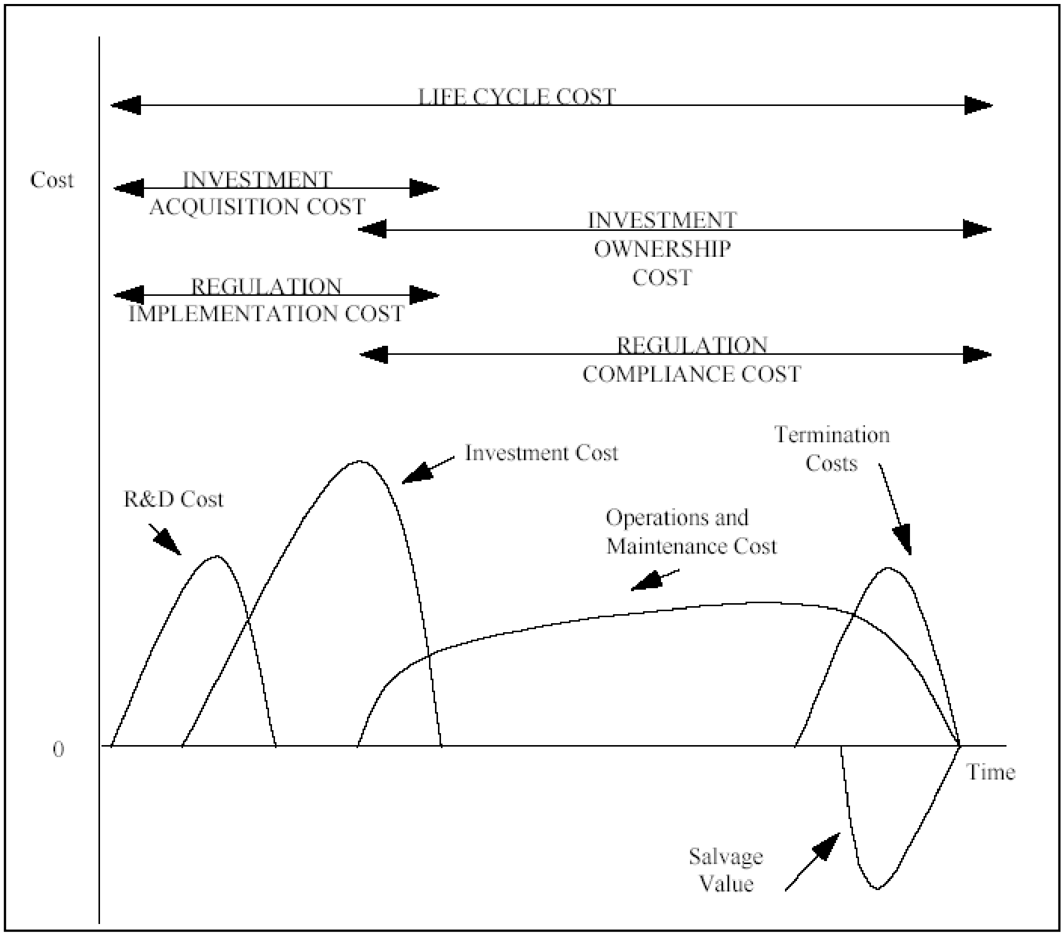

Figure 5-2: Cost Elements

There are many detailed contributors within the four major categories of cost. A set of cost factors specific to these categories for a service provider/operator can be identified upon review of the FAA's Cost Estimation Handbook[79]. Table 5-2 identifies cost factors within these categories based on information in the FAA Handbook.

From the service provider/operator perspective, although many of the systems required to provide the proposed backup solutions would utilize existing ground navigation aides, for some solutions, a significant build-out of navigation equipment might be required. However, the build-out would likely apply much of the research and development work that has already been performed within this field. Although for some solutions, there might be the possibility of supporting the termination of ground systems, this is a complex issue and was not addressed in this study. Therefore, the focus of the cost assessment from the ground service provider/operator perspective was on Investment and Operations and Maintenance costs.

[79] *FAA Life Cycle Cost Estimating Handbook*, version 0.2, Federal Aviation Administration Investment Cost Analysis Branch, ASD-410, June 3, 2002.

Table 5-2: Service Provider/Operator Cost Factors

Cost Category	Cost Factors
Research & Development	Feasibility Analysis Environmental Assessment Prototype Hardware Test Facilities Technical Experiments Operational Tests Construction Project Design and Engineering Plans Coordination with Regional Development and Transportation Plans System Design and Engineering R&D Oriented Software Modeling and Simulation Regulatory Analysis (prior to issuance of final regulation) Arrangement of Project Financing Public Outreach
Investment	Land Facilities Equipment Other regulatory implementation costs Transition costs
Operations and Maintenance	Personnel Costs Consumables Energy and Utilities Facilities Telecommunications Computer Service Costs Spares and Support Equipment Packaging, Handling and Transportation Recurring Training Recurring Travel
Termination	Dismantling Cost Transportation and Packaging Site Restoration Storage of Material Management Salvage Value (offset to termination costs)

Review of program cost information (from sources including the Current FAA Telecommunication System and Facility Description Manual, Investment Analysis Reports, etc,) led to the identification of key cost drivers that are typically considered in high-level cost assessments and that were applied to this study. These cost drivers are captured in Table 5-3.

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Table 5-3: Ground Service Provider/Operator Cost Drivers

Stakeholder	Cost Factor Category	Specific Cost Drivers
Air Navigation Service Provider	Investment	Facilities
		Equipment
	O & M	Personnel
		Energy
		Telecom
Transportation System Operator – Maritime	O&M	Personnel
		Energy
		Telecom

For user stakeholders, a significant category of cost is Investment, as aircraft within at least one user category would require new or modified equipment to support the proposed SatNav backup solutions. In the case of avionics, the Investment category is typically inclusive of Research and Development as R&D costs incurred by system developers are passed through in equipment pricing. Upon review of Investment costs as noted in articles in avionic magazines and studies addressing avionics[80], investment costs of interest included the purchase cost of equipment, installation and certification. Of secondary importance, but of significance considering the long-term nature of the investment, wais Operations & Maintenance cost. These were also considered as a cost driver for user stakeholders. A summary of the identified cost drivers of interest for the user stakeholders for application in this study are documented in Table 5-4.

Table 5-4: User Stakeholder Cost Drivers

Stakeholder	Cost Factor Category	Specific Cost Drivers
Air Carrier	Investment	New Equipment/Equipment Upgrades
		Installation/Integration/Certification (IIC) Materials
		Installation/Integration/Certification (IIC) Labor
	O&M	Parts & Labor
General Aviation – Jet/Turbo Prop	Investment	New Equipment/Equipment Upgrades
		Installation/Integration/Certification (IIC) Materials
		Installation/Integration/Certification (IIC) Labor
	O&M	Parts & Labor
General Aviation – Piston	Investment	New Equipment/Equipment Upgrades
		Installation/Integration/Certification (IIC) Materials
		Installation/Integration/Certification (IIC) Labor
	O&M	Parts & Labor
Rotorcraft	Investment	New Equipment/Equipment Upgrades
		Installation/Integration/Certification (IIC) Materials
		Installation/Integration/Certification (IIC) Labor
	O&M	Parts & Labor

To view the applicability of the defined cost drivers in the context of the proposed SatNav backup solutions considered in this study, an applicability matrix was defined. This matrix is shown in Table 5-5 where an X marks an applicable cost factor for a specific SatNav backup solution.

Table 5-5: Applicability of Cost Drivers in the Context of Candidate Backup Solutions

			D/D/I	GNSS/INS	eLORAN
ANSP	Investment	Facilities	X	X	X
		Equipment	X	X	X
	O&M		X	X	X
Maritime	Investment	Facilities			
		Equipment			

[80] For example, "Modular, Cost-Effective, Extensible Avionics Architecture for Secure, Mobile Communications", William D. Ivancic, NASA/GRC.

			D/D/I	GNSS/INS	eLORAN
	O&M				X
Commercial (Air Carrier/Air Transport Jet)	Investment	Equipment			X
		IIC Materials			X
		IIC Labor			X
	O&M		X	X	X
General Aviation – Jet/Turbo Prop	Investment	Equipment	X	X	X
		IIC Materials	X	X	X
		IIC Labor	X	X	X
	O&M		X	X	X
General Aviation – Piston	Investment	Equipment	X	X	X
		IIC Materials	X	X	X
		IIC Labor	X	X	X
	O&M		X	X	X
Rotorcraft	Investment	Equipment	X	X	X
		IIC Materials	X	X	X
		IIC Labor	X	X	X
	O&M		X	X	X

The table above implies some equipage assumptions applied in this study. These and other study assumptions are documented below. These include the following:

- The ground service provider costs may include costs incurred by an aeronautical navigation service provider and other organizations such as maritime that may operate/maintain equipment used to provide navigation services for some candidate solutions. In the cost model, costs were not decomposed to this level; rather, cost attributable to the collective ground service provider were estimated[81]
- Commercial aircraft were assumed to have INS and DME/DME currently installed (thus no cost is incurred for investment in these systems for backup solutions that utilize them); however, costs for operation/maintenance of these systems was accounted for.
- At least some percentage of general aviation (jet, turbo-prop, piston) and rotorcraft were assumed to require investment costs for navigation systems to support the identified backup candidate solutions (assumed percentages noted later).
- GPS equipment and new/upgraded Flight Management System (FMS) equipment for primary navigation supporting Area Navigation operations were assumed to be installed and therefore were not included in the backup solution cost (equipment or O&M).
- Equipment costs included a range of applicable cost factors including: receiver (transponder, antennas, cables), crew training (beyond basic RNAV training), documentation (updating flight manuals, procedures, wiring diagrams).
- Installation and certification cost reflected labor hour costs, materials needed (e.g. install kits) and costs to verify the installation; ICC material costs were calculated as a percentage of the total navigation avionics cost.

[81] eLORAN uniquely can provide PNT services to other segments of the U.S. economy. In this analysis, a conservative cost estimate is developed. The percentage of ground service provider costs that might be amortized to non-aviation users is not estimated or applied.

- Yearly maintenance for avionics was reflected as a percentage of the total equipment cost.
- Cost benefits (e.g. decommissioning of certain equipment) that may be realized for certain backup solutions was not accounted for. This benefit is difficult to estimate, as independence among the candidate backup solutions is uncertain (i.e. more than one system might be used in the future).
- Recapitalization costs for ground systems were not included in the model
- For the GNSS/INS candidate solution, this study assumed that a ground system to provide reference information used to synchronize INSs (in a backup operational mode) is needed; it was assumed that these systems would be installed at a large number of airports that support commercial operations.
- Only general aviation users/aircraft with electrical systems were considered for a backup system.
- This study assumed that a 10% additional build out of DME ground stations would be required to support 'Area Navigation' RNP operations.

5.1.2 Select Cost Methodology

To conduct a cost assessment, the methodology to be applied to perform cost estimation needed to be defined. There are a range of methods that are commonly applied; several of these approaches are defined below.

- **Parametric Method**: This method estimates costs based on various characteristics or attributes of the system. It depends on the establishment of a functional relationship between system costs and these parameters. Such relationships are typically estimated from historical data using statistical techniques.
- **Analogy Method**: This method estimates the cost of a new system by taking the cost of a similar existing one and adjusting it to reflect the differences between the two systems. This adjustment can be made either analytically or judgmentally.
- **Grass Roots Method**: This method estimates cost by developing a detailed list of parts. The cost of each of these parts is then determined and the costs of the parts are summed to determine total parts cost. Assembly and/or manufacturing costs and overhead costs are added to total parts cost to yield total cost.
- **Component Part Method**: This method is similar to the grass-roots method but proceeds at a more aggregate level of detail. It determines cost by summing the costs of all components which are known.
- **Vendor Bid Method:** This method utilizes the cost proposals or bids submitted by vendors in response to request for production proposals.

Several of the approaches defined above are appropriate for supporting an actual product development effort or the commercial implementation environment. Others are more appropriate when conducting a high-level cost assessment, such as the cost comparison of alterative solutions performed in this study. For the cost comparison of the proposed SatNav backup technologies, the

analogy method was selected. Using this method, estimates were made based on existing equipment or costs or making comparisons/extrapolations to like items. Cost data based on existing or like items could be subjectively adjusted up or down, placing heavy emphasis on the opinions of experts. This method can be quick to apply, readily understood and is based on historical data. Based on these benefits, and limitations of the study that preclude a more detailed and comprehensive cost evaluation, it was deemed an appropriate approach to apply in this study.

5.1.3 Construct Cost Model(s)

To perform the comparative cost assessment required for this study, a rough order of magnitude (ROM) Net Present Value (NPV) model was developed. NPV is a method that distills various costs of a particular project that take place over a number of time periods and discounts them back to today's dollars. The discount rate used for this analysis was simply the time value of money, which correlates essentially with expected inflation. The NPV model was useful in the context of this study as it compared options with costs falling in different time periods and provided a common measurement with which to compare the candidate solutions. For example, one candidate might require a large investment up front but then reasonably small O&M expenditures, while another would have a cost dispersion exactly the opposite (low investment/high O&M). The NPV method supports the comparison of these alternatives from a common perspective.

The cost model developed has three components. The first is the Constants and Cost Inputs. This component of the model included all of the model manual inputs (discussed further in Section 5.1.4). The second component of the cost model is the Cost Input Calculations. In this module, calculations of overall Investment and O&M costs were made for each SatNav backup option across the set of stakeholders. An excerpt of this component is shown in Figure 5-3.

		DME/DME/INS			
		Per Site/Per Aircraft	Current Number of Sites/Aircraft	Full Deployment (2020) Sites/Aircraft	Total
Ground Service Provider					
	Investment	$1,150,000	1,067	1174	122,705,000
	Facilities (per site)	$200,000			
	Equipment (per site) (procurement, T&E, doc, implementatio	$950,000			
	Equipment Upgrades (per site)				
	Operations and Maintenance	$38,000	1,067	1174	$44,600,600
	Personnel Costs				
	Energy and Utilities				
	Telecommunications				
	Other costs				
Avionics/Users					
	Commercial Jet - Air Carrier & Air Transport				
	Investment	$0	9,235	9429	$0
	Equipment (new/upgraded Nav system(s) & FMS)	$110,000	0%	% aircraft need new/upgrade DME, INS, FM	
	Equipment (new/upgraded DME & INS)	$70,000	0%	% aircraft need new/upgrade DME, INS	
	Equipment (new/upgraded DME only)	$30,000	0%	% aircraft need new/upgrade DME	
	Equipment (new/upgraded INS only)	$40,000	0%	% aircraft need new/upgrade INS	
	Equipment (new/upgraded eLORAN only)		N/A	% aircraft need new/upgrade eLORAN	
	Equipment (new/upgraded VOR only)		N/A	% aircraft need new/upgrade VOR	
	Installation/Integration/Certification (materials) (avg)	$0	based on equipment installed		
	Installation/Integration/Certification (labor) (avg)	$0	based on equipment installed		
	Operations and Maintenance	$0	9,235	9429	$0

Figure 5-3: Excerpt from the Cost Input Calculations Module

In the figure above, information specific to an individual ground equipment site or aircraft installation is combined to develop overall investment costs, accounting appropriately for the number of sites/aircraft currently equipped and those needing the defined equipment/upgrades. For example, the total ground investment cost for a DME installation (considering Facilities and Equipment) was calculated to be on the order of $1.15M. Based on the estimated build-out of DME sites required for a full DME/DME backup capability, a total ground infrastructure investment cost wais calculated. Also included is the O&M cost for ground DMEs (per site and total for all sites at full deployment).

The example above estimates the per-aircraft investments costs for DME/DME/INS on commercial jets (including equipment, installation, integration and certification). Based on the number of commercial users (current and planned growth) and number of users requiring new/upgraded equipage to support DME/DME/INS equipage (in this example assumed to be 0% for all cases), a total investment cost was calculated. As with the ground equipment, a per site/user O&M cost was combined with the total number of users to calculate a total O&M cost.

A similar process of estimating investment and O&M was applied to the other user stakeholders (not shown). This process of rolling up individual system/site equipment and O&M costs was applied across all the stakeholder sets and for each proposed Backup SatNav solution.

A final component of the cost model wais the NPV calculation module. This module included the NPV calculations for each alternative SatNav backup solution for each stakeholder. In this module, a six year investment/build-out phase of operations was applied, followed by a fifteen year operational phase of operations. The selection of the investment time phase (six years) was driven by the normal maintenance cycle for commercial aircraft as well as the typical deployment structure applied to ground installations. The operational phase time period (fifteen years) was selected to be representative of the typical long-term concept of operation horizon. The NPV value is the cost (in today's dollars) that accounts for both the investment and operational periods of operation.

NPV values for each SatNav backup solution were calculated for each stakeholder group followed by an overall NPV value for the candidate solution. An excerpt from the NPV cost module is shown in Figure 5-4. Note the following from the model:

- Investment costs (from the Cost Input Calculation module) are equally divided across the six year investment/build-out period.
- O&M costs ramp-up during the investment/build-out period for ground service providers by including a first-year O&M cost representative of current system O&M costs with a linear increase of O&M costs during the remaining five year investment period to full O&M costs.
- O&M cost ramp-up during the investment/build-out period for navigation users come in two categories: first, if the navigation system is already included on the aircraft,

the O&M costs during the investment/build-out period are the same as in the operational period; and second, if new navigation systems will be deployed on the aircraft, zero O&M costs are applied in the first investment year followed by a linear increase of O&M costs during the remaining five year investment period to full O&M costs

		Year:	ROM NPV ($M)	Investment Period/BuildOut 1	2	3	4	5	6	7
DME/DME/INS		Investment		20,450,833	20,450,833	20,450,833	20,450,833	20,450,833	20,450,833	
	Ground Service Provider	O&M		40,546,000	41,356,920	42,167,840	42,978,760	43,789,680	44,600,600	44,600,600
		Total	$787	60,996,833	61,807,753	62,618,673	63,429,593	64,240,513	65,051,433	44,600,600
	Commercia Users (	Investment		0	0	0	0	0	0	
	Air Carrier and	O&M		0	0	0	0	0	0	0
	Air Transport)	Total	$0	0	0	0	0	0	0	0
	General Aviation (Jets	Investment		185,668,680	185,668,680	185,668,680	185,668,680	185,668,680	185,668,680	
	and Turbo-Props)	O&M		0	1,700,782	3,401,564	5,102,345	6,803,127	8,503,909	8,503,909
		Total	$1,113	185,668,680	187,369,462	189,070,243	190,771,025	192,471,807	194,172,589	8,503,909
	General Aviation (Piston)	Investment		1,031,070,889	1,031,070,889	1,031,070,889	1,031,070,889	1,031,070,889	1,031,070,889	
		O&M		0	8,733,777	17,467,554	26,201,331	34,935,108	43,668,885	43,668,885
		Total	$6,136	1,031,070,889	1,039,804,666	1,048,538,443	1,057,272,220	1,066,005,997	1,074,739,773	43,668,885
	Rotorcraft	Investment		69,109,788	69,109,788	69,109,788	69,109,788	69,109,788	69,109,788	
		O&M		0	585,401	1,170,801	1,756,202	2,341,602	2,927,003	2,927,003
		Total	$411	69,109,788	69,695,189	70,280,589	70,865,990	71,451,391	72,036,791	2,927,003
	Total		$8,448							

Figure 5-4: Excerpt from the NPV Cost Module

In the figure above, the columns on the left identify the candidate SatNav backup solution and the stakeholder sets for which costs were calculated. The rough order of magnitude (ROM) NPV cost evaluation results were provided next. This is the output of the model that provides costs in today's dollars representative of total investment and a fifteen year O&M period for each stakeholder set for each candidate backup solution. The columns to the right, numbered from 1 through 21 represent a six year investment period followed by a fifteen year operation period. Costs per year were identified and were used as inputs to the NPV calculations. Note that the figure above shows only the first year of the fifteen year operational period included in the model.

Outputs of the NPV Cost module include investment costs and 15 year O&M costs per stakeholder set per SatNav backup solution, as well as the combined NPV for each proposed backup solution (considering all stakeholder costs).

5.1.4 Collect Data

As noted above, a range of data elements required for the cost assessment was captured in the Constants and Cost Inputs cost module. These inputs included:

- Number of aircraft within each user category (present-day and growth through 2020)
- Number of ground navigation stations (present-day numbers and requirements for full Backup capability)
- Navigation Equipment Costs (ground station and avionics)
- Navigation Equipment Installation Costs
- Certification Costs (as a percentage of equipment cost)
- Annual maintenance costs

The sources used for the input values ranged from documented values in FAA or user databases and studies; to discussion with experts in the aviation field (e.g. representatives of equipment manufacturers); to applied engineering assumptions.

The data inputs included a mix of data elements from validated references, data elements obtained from stakeholder discussions or documents but not validated, and applied engineering estimates. As a result, the confidence level associated with the data inputs varied. A summary of the key input data, source applied to define the data value, and confidence level indication is provided in Table 5-7.

Table 5-6: Key Cost Model Data Inputs

	Data Input to Cost Model	Data Source(s)	Confidence Level
1	Number of Aircraft	FAA forecast data and AOPA scorecard data	High
2	Aircraft growth rate	FAA forecast data and AOPA scorecard data	High
3	Percent aircraft DME equipped	AOPA scorecard data, discussions with stakeholders and applied engineering assumptions (assumed all commercial users are DME equipped; 40% GA-Jet/turbo equipped and 0% GA-piston/rotorcraft equipped)	Medium
4	Percent aircraft INS equipped	Discussions with stakeholders and applied engineering assumptions (assumed all commercial users are INS equipped; 0% GA-Jet/turbo equipped and 0% GA-piston/rotorcraft equipped)	Medium
5	Percent aircraft eLORAN equipped	Discussions with stakeholders and applied engineering assumptions (assumed no users are equipped)	High
6	Percent aircraft VOR equipped	Discussions with stakeholders and applied engineering assumptions (assumed 10% commercial users are VOR equipped; 85% GA-Jet/turbo equipped and 90% GA-piston/rotorcraft equipped)	Medium
7	Navigation ground site F&E costs for: DME; INS ground reference facility[82]; eLORAN upgrades; eLORAN new site; VOR (per site)	Airport authority planning studies; navigation system engineering studies and applied engineering assumptions (DME approx $1.2M; INS ground reference site approx $400K; eLORAN upgrade approx $4M; eLORAN new site approx $15M; VOR approx $1.2M)	Medium
8	Navigation ground site O&M costs for: DME; INS ground reference facility; eLORAN; VOR (per site)	FAA Technical Briefing material (e.g. FAA NAV TAC); Navigation studies (e.g. GPS Backup for Position, Navigation and Timing; Transition Strategy for Navigation and Surveillance); Discussions with FAA; and applied engineering assumptions (DME approx $38K; INS ground reference facility approx $35K; eLORAN approx $500K; VOR approx $55K)	Medium

[82] The INS ground reference facility concept is to provide INS systems with an accurate surface point position reference at arrival to enable surface operations, and at departure to enable surface navigation and terminal departure capability in the event of a terminal area disruption to GNSS. This component is highly conceptual.

	Data Input to Cost Model	Data Source(s)	Confidence Level
9	Avionics equipment costs for DME, INS, eLORAN, VOR	Discussions with avionics manufacturers, installers and mechanics and applied engineering assumptions (DME approx $30K (commercial & GA-jet/turbo) and $10K (GA-piston/rotor-craft); INS approx $40K (commercial jet) and $20K (GA-jet/turbo/rotorcraft); eLORAN 30K (commercial & GA-jet/turbo) and $15K (GA-piston/rotor-craft); VOR approx $40K (commercial) and $20K (GA-jet/turbo) and $15K (GA-piston/rotor-craft))	Medium
10	Avionics installation, integration, certification labor cost (labor hours/rates and installation time per navigation system, or other methodology)	Applied engineering assumptions based on review of labor/installation cost information in user forums and stakeholder discussions (labor cost $150/hr commercial and $100/hr GA; 40 hours IIC time for navigation system)	Low/Medium
11	Avionics installation, integration, certification materials cost	Discussion with stakeholders, review of similar cost studies and applied engineering assumptions – IIC material cost applied as a percentage of equipment cost (15% of equipment cost)	Low/Medium
12	Number of current DME sites	FAA equipment information	High
13	Percent increase in DME sites for full Backup capability	Applied engineering assumption	Medium
14	Required number of ground reference stations required to support the GNSS/INS backup solution	Applied high-level engineering assumptions (assumed reference stations would be implemented at 250 largest airports)	Low
15	Number of current eLORAN sites	Assumption based on total Coast Guard equipment operations	Medium
16	Percent increase in eLORAN sites for full Backup capability	Review of technical studies and applied engineering assumption	Medium

A view of the data inputs applied and captured in the actual cost model is shown in Figure 5-5.

User Categories	Number of Aircraft (2006)	Growth Rate (through 2025)	Total by 2025	Assumed % Integrated FMS Equipped	% FMS Equipped also with DME/INS	% FMS Not Equipped but with DME/INS	% Aircraft FMS/INS equippped without DME	% Aircraft FMS/DME equipped without INS	% FMS Equiped with INS	%FMS Not Equipped with INS	Assumed %FMS Equiped with eLORAN	Assumed %FMS Not Equiped with eLORAN	Assumed %FMS equiped with VOR	Assumed FMS not equiped with VOR
Air Carrier Jet	9,235	0.021	9,429	100%	100%	0%	0%	0%	100%	0%	0%	0%	10%	0%
GA - Jet/Turbo-Prop	16,658	0.041	17,341	100%	0%	0%	0%	0%	10%	0%	0%	0%	85%	85%
GA - Piston	142,569	0.003	142,997	100%	0%	0%	0%	0%	0%	0%	0%	0%	90%	90%
Rotor-Craft	9,566	0.036	9,900	100%	0%	0%	0%	0%	0%	0%	0%	0%	90%	90%

Equipment Costs

DME	Ground Facilities	$200,000.00	Estimated based on facility costs for similar FAA systems (e.g. ground radio)
	Ground Equipment	$950,000.00	Estimate based on NAPLES FL Report
	Commercial Jet	$30,000.00	Estimated based on discussion with stakeholders/manufacturers
	GA - Jet/Turbo-Prop	$30,000.00	Estimated based on discussion with stakeholders/manufacturers
	GA - Piston/Rotor-craft	$10,000.00	Estimated based on discussion with stakeholders/manufacturers
INS	Ground Reference Facilities	$100,000.00	Estimate
	Ground Reference Equipment	$300,000.00	Estimate
	Commercial Jet	$40,000.00	Estimated based on discussion with stakeholders/manufacturers
	GA - Jet/Turbo-Prop	$20,000.00	Estimated based on discussion with stakeholders/manufacturers (including Honeywell)
	GA - Piston/Rotor-craft	$20,000.00	
eLORAN	Ground Facilities	$200,000.00	Estimated based on facility costs for similar FAA systems (e.g. ground radio)
	Ground Site Upgrades	$7,000,000.00	Estimate
	New Ground Sites	$15,000,000.00	Estimate
	Commercial Jet	$30,000.00	Estimated based on discussion with stakeholders/manufacturers
	GA - Jet/Turbo-Prop	$30,000.00	Estimated based on discussion with stakeholders/manufacturers
	GA - Piston/Rotor-craft	$15,000.00	Estimated based on discussion with stakeholders/manufacturers
VOR	Ground Facilities	$200,000.00	Estimated based on facility costs for similar FAA systems (e.g. ground radio)
	Ground Equipment	$1,000,000.00	Estimate
	Commercial Jet	$40,000.00	Estimated based on discussion with stakeholders/manufacturers
	GA - Jet/Turbo-Prop	$20,000.00	Estimated based on discussion with stakeholders/manufacturers
	GA - Piston/Rotor-craft	$15,000.00	Estimated based on discussion with stakeholders/manufacturers
ILS/GS	Ground Facilities		
	Ground Equipment		
	Commercial Jet	$40,000.00	Estimated based on discussion with stakeholders/manufacturers
	GA - Jet/Turbo-Prop	$40,000.00	Estimated based on discussion with stakeholders/manufacturers
	GA - Piston/Rotor-craft	$20,000.00	Estimated based on discussion with stakeholders/manufacturers
GPS	Commercial Jet	$50,000.00	Estimated based on discussion with stakeholders/manufacturers
	GA - Jet/Turbo-Prop	$30,000.00	Estimated based on discussion with stakeholders/manufacturers
	GA - Piston/Rotor-craft	$20,000.00	Estimated based on discussion with stakeholders/manufacturers
FMS	Commercial Jet	$40,000.00	
	GA - Jet/Turbo-Prop	$40,000.00	Estimated based on discussion with stakeholders/manufacturers
	GA - Piston/Rotor-craft	$40,000.00	Estimated based on discussion with stakeholders/manufacturers

Installation Labor Cost	Hourly Install Labor Cost		Navigation Equipment Install/Integrate/ Certify Time (hours)		FMS Equipment Install/Integrate/ Certify Time (hours)	
Labor Costs - Commercial (/hr)	$150	Estimate based on	40	Estimate based	80	Conservative
Labor Costs - GA (/hr)	$100	Estimate based on	40	Estimate based	80	Conservative

Installation/Integration/ Certification Non-Labor Costs (e.g. install kits/service bulletins)	% Hardware Cost	
Certification Costs - Commercial	15%	Derived from values used in other technical evaluation reports (e.g. reference 3)
Certification Costs - GA	15%	Derived from values used in other technical evaluation reports (e.g. reference 3)

Maintenance Costs	Yearly O&M	
DME	38,000	Reference 4 and 5
INS Reference Station	35,000	Estimated (same order of magnitude as DME)
eLORAN	825,000	Rough division of O&M estimates (reference 6) by Number of Ground Stations (24)
VOR	93,000	Reference 7
Avionics (% hardware cost)	1%	Reference 3 uses a value of approximately 10%; however, with discussion with stakeholders/manufacturers, value was adjusted to 1%

Build-Out/Install Requirements

DME	Ground Sites	1,067	Draft Report
	Ground Site Growth	10%	Estimate
INS	Ground Reference Sites-	250	Estimated
	Ground Site Growth	N/A	Assumed to be new ground reference stations
	Percent GA-Piston/Rotor-Craft	0%	copied from cell above (H8)
eLORAN	Ground Sites - Upgraded	12	Assumed: 50% of Coast Guard operated LORAN stations upgraded to eLORAN
	Ground Sites (Total)	24	
	Upgraded Ground Site	17%	Estimate
VOR	Ground Sites	1,112	From Draft Report
	Ground Site Growth	0%	Estimate

References

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3 Roadmap for the Implementation of Datalink Services in European Air Traffic Management (ATM): Technology Assessment, Helios Tech Ltd, 28 February 2003.
4 Status Report, Global Navigation Satellite System (GNSS) Augmentation Audit and Cost Benefit Analysis, Airservics Aulstalia, April 1997
5 May 1, 2007 Briefing by FAA's NAV TAC
6 Independent Assessment Team (IAT) Summary of Initial Findings on eLoran, 20 March 2007, v4.
7 FAA Cost Analyst report of FY2004 VOR avg O&M cost

Figure 5-5: Summary of Data Input in SatNav Backup Solution Cost Model

5.1.5 Develop Estimates

Using the model and data inputs described above, a set of rough order of magnitude NPV cost estimates to support comparative assessment of SatNav backup solutions were developed. A full view of the Cost Model Input Module is shown in Figure 5-6. This module combined per site/per user investment costs for the larger stakeholder set (applying percentages of users that need new equipment) to calculate overall investment and yearly operation/maintenance costs.

The investment and operation/maintenance costs were then considered in the context of an investment period (described previously as 6 years) and a 15 year operations period. This is the full NPV Cost Model (for calculation of life cycle costs). Although this module included initial investment costs and operating costs for a 15 year period, for illustration purposes only the first three years of the operational phase are shown (the remaining years have an identical cost structure to those years shown). A view of this module is provided in Figure 5-7.

	DME/DME/INS			GPS/INS				eLORAN			
	Per Site/Per Aircraft	Current Number of Sites/Aircraft	Full Deployment (2020) Sites/Aircraft	Per Site/Per Aircraft	Current Number of Sites/Aircraft	Full Deployment (2020) Sites/Aircraft	Total	Per Site/Per Aircraft	Current Number of Sites/Aircraft	Full Deployment (2020) Sites/Aircraft	Total
Ground Service Provider											144,556,800
Investment	$1,150,000	1,067	1174	$400,000	0	250	100,000,000	$15,200,000	24	28	60,556,800
Facilities (per site)	$200,000			$100,000				$200,000			
Equipment (per site) (procurement, T&E, doc, implementatic	$950,000			$300,000				$15,000,000			
Equipment Upgrades (per site)								$7,000,000	12	24	84,000,000
Operations and Maintenance	$38,000	1,067	1174	$35,000	0	250	$8,750,000	$825,000	24	28	$23,086,800
Personnel Costs											
Energy and Utilities											
Telecommunications											
Other costs											
Avionics/Users											
Commercial Jet - Air Carrier & Air Transport											
Investment	$0	9,235	9429	$0	9,235	9429	$0	varies	9,235	9429	$381,871,868
Equipment (new/upgraded Nav system(s) & FMS)	$110,000	0%	% aircraft need new/upgrade DME, INS, FN	$80,000	0%	% aircraft need new/upgrade INS, FM		$70,000	0%	% aircraft need new/upgrade eLORAN, FN	
Equipment (new/upgraded DME & INS)	$70,000	0%	% aircraft need new/upgrade DME, INS		N/A	% aircraft need new/upgrade DME, INS			N/A	% aircraft need new/upgrade DME, INS	
Equipment (new/upgraded DME only)	$30,000	0%	% aircraft need new/upgrade DME		N/A	% aircraft need new/upgrade DME			N/A	% aircraft need new/upgrade DME	
Equipment (new/upgraded INS only)	$40,000	0%	% aircraft need new/upgrade INS	$40,000	0%	% aircraft need new/upgrade INS			N/A	% aircraft need new/upgrade INS	
Equipment (new/upgraded eLORAN only)		N/A	% aircraft need new/upgrade eLORAN		N/A	% aircraft need new/upgrade eLORAN		$30,000	100%	% aircraft need new/upgrade eLORAN	
Equipment (new/upgraded VOR only)		N/A	% aircraft need new/upgrade VOR		N/A	% aircraft need new/upgrade VOR			N/A	% aircraft need new/upgrade VOR	
Installation/Integration/Certification (materials) (avg)	$0	based on equipment installed		$0	based on equipment installed			$4,500	based on equipment installed		
Installation/Integration/Certification (labor) (avg)	$0	based on equipment installed		$0	based on equipment installed			$6,000	based on equipment installed		
Operations and Maintenance	$0	9,235	9429	$0	9,235	9429	$0	$300	9,235	9429	$2,828,681
GA-Jet and Turbo-Prop											
Investment	varies	16,658	17008	varies	16,658	17008	$402,575,052	varies	16,658	17008	$688,816,629
Equipment (new/upgraded Nav system(s) & FMS)	$90,000	0%	% aircraft need new/upgrade DME, INS, FN	$80,000	0%	% aircraft need new/upgrade INS, FM		$70,000	0%	% aircraft need new/upgrade eLORAN, FN	
Equipment (new/upgraded DME & INS)	$50,000	100%	% aircraft need new/upgrade DME, INS		N/A	% aircraft need new/upgrade DME, INS			N/A	% aircraft need new/upgrade DME, INS	
Equipment (new/upgraded DME only)	$30,000	0%	% aircraft need new/upgrade DME		N/A	% aircraft need new/upgrade DME			N/A	% aircraft need new/upgrade DME	
Equipment (new/upgraded INS only)	$20,000	0%	% aircraft need new/upgrade INS	$20,000	90%	% aircraft need new/upgrade INS			N/A	% aircraft need new/upgrade INS	
Equipment (new/upgraded eLORAN only)		N/A	% aircraft need new/upgrade eLORAN		N/A	% aircraft need new/upgrade eLORAN		$30,000	100%	% aircraft need new/upgrade eLORAN	
Equipment (new/upgraded VOR only)		N/A	% aircraft need new/upgrade VOR		N/A	% aircraft need new/upgrade VOR			N/A	% aircraft need new/upgrade VOR	
Installation/Integration/Certification (materials) (avg)	$7,500	based on equipment installed		$2,700	based on equipment installed			$4,500	based on equipment installed		
Installation/Integration/Certification (labor) (avg)	$8,000	based on equipment installed		$3,600	based on equipment installed			$6,000	based on equipment installed		
Operations and Maintenance	$500	16,658	17008	$180	16,658	17008	$3,061,407	$300	16,658	17008	$5,102,345
GA-Piston											
Investment	varies	142,569	145563	varies	142,569	145563	$3,930,199,623	varies	142,569	145563	$3,093,212,666
Equipment (new/upgraded Nav system(s) & FMS)	$70,000	0%	% aircraft need new/upgrade DME, INS, FN	$60,000	0%	% aircraft need new/upgrade INS, FM		$55,000	0%	% aircraft need new/upgrade eLORAN, FN	
Equipment (new/upgraded DME & INS)	$30,000	100%	% aircraft need new/upgrade DME, INS		N/A	% aircraft need new/upgrade DME, INS			N/A	% aircraft need new/upgrade DME, INS	
Equipment (new/upgraded DME only)	$10,000	0%	% aircraft need new/upgrade DME		N/A	% aircraft need new/upgrade DME			N/A	% aircraft need new/upgrade DME	
Equipment (new/upgraded INS only)	$20,000	0%	% aircraft need new/upgrade INS	$20,000	100%	% aircraft need new/upgrade INS			N/A	% aircraft need new/upgrade INS	
Equipment (new/upgraded eLORAN only)		N/A	% aircraft need new/upgrade eLORAN		N/A	% aircraft need new/upgrade eLORAN		$15,000	100%	% aircraft need new/upgrade eLORAN	
Equipment (new/upgraded VOR only)		N/A	% aircraft need new/upgrade VOR		N/A	% aircraft need new/upgrade VOR			N/A	% aircraft need new/upgrade VOR	
Installation/Integration/Certification (materials) (avg)	$4,500	based on equipment installed		$3,000	based on equipment installed			$2,250	based on equipment installed		
Installation/Integration/Certification (labor) (avg)	$8,000	based on equipment installed		$4,000	based on equipment installed			$4,000	based on equipment installed		
Operations and Maintenance	$300	142,569	145563	$200	142,569	145563	$29,112,590	$150	142,569	145563	$21,834,442
GA-Rotorcraft											
Investment	varies	9,556	9757	varies	9,556	9757	$263,430,252	varies	9,556	9757	$207,329,365
Equipment (new/upgraded Nav system(s) & FMS)	$70,000	0%	% aircraft need new/upgrade DME, INS, FN	$60,000	0%	% aircraft need new/upgrade INS, FM		$55,000	0%	% aircraft need new/upgrade eLORAN, FN	
Equipment (new/upgraded DME & INS)	$30,000	100%	% aircraft need new/upgrade DME, INS		N/A	% aircraft need new/upgrade DME, INS			N/A	% aircraft need new/upgrade DME, INS	
Equipment (new/upgraded DME only)	$10,000	0%	% aircraft need new/upgrade DME		N/A	% aircraft need new/upgrade DME			N/A	% aircraft need new/upgrade DME	
Equipment (new/upgraded INS only)	$20,000	0%	% aircraft need new/upgrade INS	$20,000	100%	% aircraft need new/upgrade INS			N/A	% aircraft need new/upgrade INS	
Equipment (new/upgraded eLORAN only)		N/A	% aircraft need new/upgrade eLORAN		N/A	% aircraft need new/upgrade eLORAN		$15,000	100%	% aircraft need new/upgrade eLORAN	
Equipment (new/upgraded VOR only)		N/A	% aircraft need new/upgrade VOR		N/A	% aircraft need new/upgrade VOR			N/A	% aircraft need new/upgrade VOR	
Installation/Integration/Certification (materials) (avg)	$4,500	based on equipment installed		$3,000	based on equipment installed			$2,250	based on equipment installed		
Installation/Integration/Certification (labor) (avg)	$8,000	based on equipment installed		$4,000	based on equipment installed			$4,000	based on equipment installed		
Operations and Maintenance	$300	9,556	9757	$200	9,556	9757	$1,951,335	$150	9,556	9757	$1,463,501

Figure 5-6: Cost Model Input Module

Variables	
Discount Rate	3.000%

			ROM	Investment Period/BuildOut								
		Year:	NPV ($M)	1	2	3	4	5	6	7	8	9
DME/DME/INS		Investment		20,450,833	20,450,833	20,450,833	20,450,833	20,450,833	20,450,833			
	Ground Service Provider	O&M		40,546,000	41,356,920	42,167,840	42,978,760	43,789,680	44,600,600	44,600,600	44,600,600	44,600,600
		Total	$787	60,996,833	61,807,753	62,618,673	63,429,593	64,240,513	65,051,433	44,600,600	44,600,600	44,600,600
	Commercia Users (	Investment		0	0	0	0	0	0			
	Air Carrier and	O&M		0	0	0	0	0	0	0	0	0
	Air Transport)	Total	$0	0	0	0	0	0	0	0	0	0
	General Aviation (Jets	Investment		185,668,680	185,668,680	185,668,680	185,668,680	185,668,680	185,668,680			
	and Turbo-Props)	O&M		0	1,700,782	3,401,564	5,102,345	6,803,127	8,503,909	8,503,909	8,503,909	8,503,909
		Total	$1,113	185,668,680	187,369,462	189,070,243	190,771,025	192,471,807	194,172,589	8,503,909	8,503,909	8,503,909
	General Aviation (Piston)	Investment		1,031,070,889	1,031,070,889	1,031,070,889	1,031,070,889	1,031,070,889	1,031,070,889			
		O&M		0	8,733,777	17,467,554	26,201,331	34,935,108	43,668,885	43,668,885	43,668,885	43,668,885
		Total	$6,136	1,031,070,889	1,039,804,666	1,048,538,443	1,057,272,220	1,066,005,997	1,074,739,773	43,668,885	43,668,885	43,668,885
	Rotorcraft	Investment		69,109,788	69,109,788	69,109,788	69,109,788	69,109,788	69,109,788			
		O&M		0	585,401	1,170,801	1,756,202	2,341,602	2,927,003	2,927,003	2,927,003	2,927,003
		Total	$411	69,109,788	69,695,189	70,280,589	70,865,990	71,451,391	72,036,791	2,927,003	2,927,003	2,927,003
	Total		$8,448									
GPS/INS		Investment		16,666,667	16,666,667	16,666,667	16,666,667	16,666,667	16,666,667			
	Ground Service Provider	O&M		0	1,750,000	3,500,000	5,250,000	7,000,000	8,750,000	8,750,000	8,750,000	8,750,000
		Total	$201	16,666,667	18,416,667	20,166,667	21,916,667	23,666,667	25,416,667	8,750,000	8,750,000	8,750,000
	Commercia Users (	Investment		0	0	0	0	0	0			
	Air Carrier and	O&M		0	0	0	0	0	0	0	0	0
	Air Transport)	Total	$0	0	0	0	0	0	0	0	0	0
	General Aviation (Jets	Investment		67,095,842	67,095,842	67,095,842	67,095,842	67,095,842	67,095,842			
	and Turbo-Props)	O&M		0	612,281	1,224,563	1,836,844	2,449,126	3,061,407	3,061,407	3,061,407	3,061,407
		Total	$402	67,095,842	67,708,123	68,320,405	68,932,686	69,544,968	70,157,249	3,061,407	3,061,407	3,061,407
	General Aviation (Piston)	Investment		655,033,271	655,033,271	655,033,271	655,033,271	655,033,271	655,033,271			
		O&M		0	5,822,518	11,645,036	17,467,554	23,290,072	29,112,590	29,112,590	29,112,590	29,112,590
		Total	$3,916	655,033,271	660,855,788	666,678,306	672,500,824	678,323,342	684,145,860	29,112,590	29,112,590	29,112,590
	Rotorcraft	Investment		43,905,042	43,905,042	43,905,042	43,905,042	43,905,042	43,905,042			
		O&M		0	390,267	780,534	1,170,801	1,561,068	1,951,335	1,951,335	1,951,335	1,951,335
		Total	$262	43,905,042	44,295,309	44,685,576	45,075,843	45,466,110	45,856,377	1,951,335	1,951,335	1,951,335
	Total		$4,781									
eLORAN		Investment		24,092,800	24,092,800	24,092,800	24,092,800	24,092,800	24,092,800			
	Ground Service Provider	O&M		19,800,000	20,457,360	21,114,720	21,772,080	22,429,440	23,086,800	23,086,800	23,086,800	23,086,800
		Total	$477	43,892,800	44,550,160	45,207,520	45,864,880	46,522,240	47,179,600	23,086,800	23,086,800	23,086,800
	Commercial Users (	Investment		63,645,311	63,645,311	63,645,311	63,645,311	63,645,311	63,645,311			
	Air Carrier and	O&M		0	565,736	1,131,472	1,697,208	2,262,944	2,828,681	2,828,681	2,828,681	2,828,681
	Air Transport)	Total	$380	63,645,311	64,211,047	64,776,783	65,342,520	65,908,256	66,473,992	2,828,681	2,828,681	2,828,681
	General Aviation (Jets	Investment		114,802,772	114,802,772	114,802,772	114,802,772	114,802,772	114,802,772			
	and Turbo-Props)	O&M		0	1,020,469	2,040,938	3,061,407	4,081,876	5,102,345	5,102,345	5,102,345	5,102,345
		Total	$686	114,802,772	115,823,241	116,843,710	117,864,179	118,884,648	119,905,117	5,102,345	5,102,345	5,102,345
	General Aviation (Piston)	Investment		515,535,444	515,535,444	515,535,444	515,535,444	515,535,444	515,535,444			
		O&M		0	4,366,888	8,733,777	13,100,665	17,467,554	21,834,442	21,834,442	21,834,442	21,834,442
		Total	$3,068	515,535,444	519,902,333	524,269,221	528,636,110	533,002,998	537,369,887	21,834,442	21,834,442	21,834,442
	Rotorcraft	Investment		34,554,894	34,554,894	34,554,894	34,554,894	34,554,894	34,554,894			
		O&M		0	292,700	585,401	878,101	1,170,801	1,463,501	1,463,501	1,463,501	1,463,501
		Total	$206	34,554,894	34,847,594	35,140,295	35,432,995	35,725,695	36,018,396	1,463,501	1,463,501	1,463,501
	Total		$4,818									

Figure 5-7: NPV Cost Module (3 of 15 operational years shown)

A summary of the model outputs is provided in Table 5-7.

Table 5-7: Summary of Cost Assessment Calculation Results

Candidate	Stakeholder	Estimate Relative Costs		Notes
		Approx Per User/ Per Site Investment	Preliminary NPV	
DME/DME/INS	Ground Service Provider	$1,150 K	$787 M	Assume some build out of DME ground sites is required (approx equal to 10% of current number of sites)
	Commercial – Jet	$0	$0 M	Assume all users are DME/INS equipped with appropriate FMS to blend signal inputs
	GA – Jet/Turbo	$32 - 62 K	$851 M	Investment cost includes new DME/INS systems
	GA – Piston	$43 K	$6136 M	Assume all users can implement INS (although new smaller/lighter INS systems may become available, this is a very conservative assumption from the cost perspective); Investment costs include new DME/INS systems
	Rotorcraft	$43 K	$411 M	Assume all users can implement INS (although new smaller/lighter INS systems may become available, this is a very conservative assumption from the cost perspective);
	TOTAL	N/A	$8185 M	
GNSS/INS	Ground Service Provider	$400 K	$201 M	Per site investment costs are for a base set ground-based reference stations use to synchronize INS in the surface environment when GNSS is not available
	Commercial – Jet	$0	$0 M	Assume all users are INS equipped
	GA – Jet/Turbo	$26 K	$402 M	Investment costs include new INS system
	GA – Piston	$27 K	$3916 M	Assume all users can implement INS (although new smaller/lighter INS systems may become available, this is a very conservative assumption from the cost perspective); Investment costs include new INS
	Rotorcraft	$27 K	$262 M	Assume all users can implement INS (although new smaller/lighter INS systems may become available, this is a very conservative assumption from the cost perspective);
	TOTAL	N/A	$4781 M	

Candidate	Stakeholder	Estimate Relative Costs		Notes
		Approx Per User/ Per Site Investment	Preliminary NPV	
eLORAN	Ground Service Provider	$15,200 K	$477 M	Assume some build out of eLORAN ground sites is required with a significant per-site cost as indicated; note that this cost estimate does account for plan site upgrades already started
	Commercial – Jet	$41 K	$380 M	Investment costs include new eLORAN avionics
	GA – Jet/Turbo	$41 K	$686 M	Investment costs include new eLORAN avionics
	GA – Piston	$22 K	$3068 M	Investment costs include new eLORAN avionics
	Rotorcraft	$22 K	$206 M	Investment costs include new eLORAN avionics
	TOTAL	N/A	$4818 M	

5.2 COST OBSERVATIONS

A NPV cost model that can be used to examine the relative costs of proposed Backup SatNav solutions for applicable stakeholders was developed. Using this model, a preliminary set of costs covering an "investment" period and a fifteen year "operations" period was estimated. Before discussing specific results, an important element to note that is not captured in the comparative cost analysis is the percentage of GA users that will equip with a SatNav backup solution that meets the technical requirements of this study. For GA users not requiring access to managed air space, this equipage might be considered optional. With current plans to maintain a minimum VOR network, it is uncertain what percentage will even equip with GNSS, the primary navigation method assumed in this study.

Another important point to keep in mind when considering results of the cost assessment is one of the ground rules applied. Specifically, one objective of this assessment was to develop a cost model that will support the relative comparison of backup solutions. To do this in as equitable manner as possible, it was assumed that some build-out of ground infrastructure is required and all users within each stakeholder set will equip to participate (100% equipage). Note that this percentage of users participating is conservative and will overestimate overall actual user equipage costs. Additionally, the ground infrastructure needs are not validated. However, provided cost outputs, per user and overall NPV for total user set investment and operational period, can provide some understanding of what are the cost drivers and how the candidate SatNav backup solutions compare with each other.

For the DME/DME/INS backup solution, the per participant investment costs varied. For the ground service provider a per-site investment of approximately $1M is required to establish each new DME site, with a total investment of $123M estimated to support build-out. For users, commercial jets have the least investment as most are identified as having DME/DME and INS capability currently installed. For

general aviation, per user investment costs are estimated to be on the order of $30 - 60 K, where the range is indicative of a need for either DME or INS; or a need for both new systems. Note, that it was assumed that INS systems of suitable size/weight will be available to install on general aviation aircraft and rotorcraft included in the aircraft counts applied in this study. Although smaller/lighter INS systems are being considered by manufacturers, it is a conservative assumption to assume that they will be suitable for all airframes. It is likely that some aircraft will not be able to install INS systems, which may limit their participation in certain airspace environments. Note that the total investment costs per user stakeholder for DME varies by aircraft type, ranging from approx $400 M to $6000 M, where the variation is driven by the number of users within each stakeholder group.

For the GNSS/INS backup solution, again the per user investment costs varied considerable. For the ground service provider a per-site investment cost of approximately $400 K was calculated for a conceptual concept of an INS ground reference facility. This would provide INS systems with an accurate surface position point reference at arrival to enable surface operations and at departure to enable surface navigation and terminal departure capability in the event of a terminal area disruption to GNSS. A total investment of $100 M was estimated to establish this ground reference capability. For users, commercial jets require the least new investment as most were identified as having an INS capability currently installed. For general aviation, per user investment costs were estimated to be on the order of $30 K, which accounts for the installation of INS equipment. As noted previously, it was assumed that INS systems of suitable size/weight will be available to install on general aviation aircraft and rotorcraft included in the aircraft counts applied in this study (a conservative assumption from a cost perspective). It is likely that some aircraft will not be able to install INS systems, which may limit their participation in certain airspace environments. Note that the total investment costs per user stakeholder for GNSS/INS varies by aircraft type, ranging from approx $260 M to $4000 M, where the variation is again driven by the number of users within each stakeholder group.

For the eLORAN backup solution, all of the users would incur some investment costs. For the ground service provider a per-new-site investment cost of approximately $15.2 M was calculated, where a few new sites were estimated to be required. The investment costs also accounted for upgrades to approximately 50% of the current sites that have not yet been upgraded, with a per-site cost of approximately $7 M. A total investment of $145 M was estimated for this solution for the ground service provider. For this solution (unlike the previous two), commercial jets would have an investment cost to account for, namely implementation of eLORAN avionics. The per-user costs were estimated to be on the order of $40 K per users, with a total commercial user group investment of approximately $380 M. For general aviation, per user investment costs were estimated to be on the order of $20 - 40 K, where the range accounts for basic avionics packages for piston and rotorcraft and more sophisticated avionics for integration into jet and turboprop aircraft. The total investment costs for General Aviation/rotorcraft stakeholders for eLORAN varied by aircraft type, ranging from approx $210 M to $3000 M, where, as in the cases above, the variation was driven by the number of users within each stakeholder group

As noted above, the per stakeholder investment costs varied significantly for different candidate backup solutions. Considering a life cycle cost (i.e. an investment period and operation/maintenance period), the cost model shows there are significant costs differences between candidate when considered from different stakeholder perspectives and overall (considering all stakeholder combined). Some observations include:

- For ground service providers, each solution provides a different life cycle cost, with DME/DME/INS having the highest overall cost, eLORAN second and GNSS/INS the least
- For the commercial jet stakeholder set, the DME/DME/INS and GNSS/INS solutions have little to no costs and eLORAN has the highest cost impact on this user group
- For the GA – jet/turboprop stakeholders, most individual users incur about the same cost per solution, with some advantage (in the cost perspective) given to GNSSINS, as some users may already have INS installed; overall, DME/DME/INS is identified as a higher cost solution as some users would need to install both DME and INS for this solution
- For GA – piston and rotorcraft, GNSS/INS and eLORAN have similar overall cost performance; DME/DME/INS was identified as an overall more costly solution as many users would need to install both DME and INS for this candidate

Again, there is not one solution that provides the least or most costly solution to all stakeholder groups, rather, some solutions are least expensive to some stakeholder while most expensive to others, and vice-versa. The cost calculations and associated cost observations supported the evaluation of candidate solutions to evaluation criteria (one of which is life cycle cost) as discussed in the following section.

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6. BACKUP SOLUTION EVALUATION

6.1 EVALUATION APPROACH

Section 2 defined the overall approach for the assessment of SatNav backup alternatives, a methodology based on the Analytical Hierarchy Process or AHP. This included derivation of evaluation criteria (as discussed in Section 3); performing a screening process by defining candidate alternatives, identifying threshold criteria; screening alternatives through evaluation against threshold criteria (as described in Section 4); and finally, assessing candidates brought forward from the screening process against defined decision factors – the topic of this section. The work to assess the screened candidates with the defined decision factors is shown in Figure 6-1.

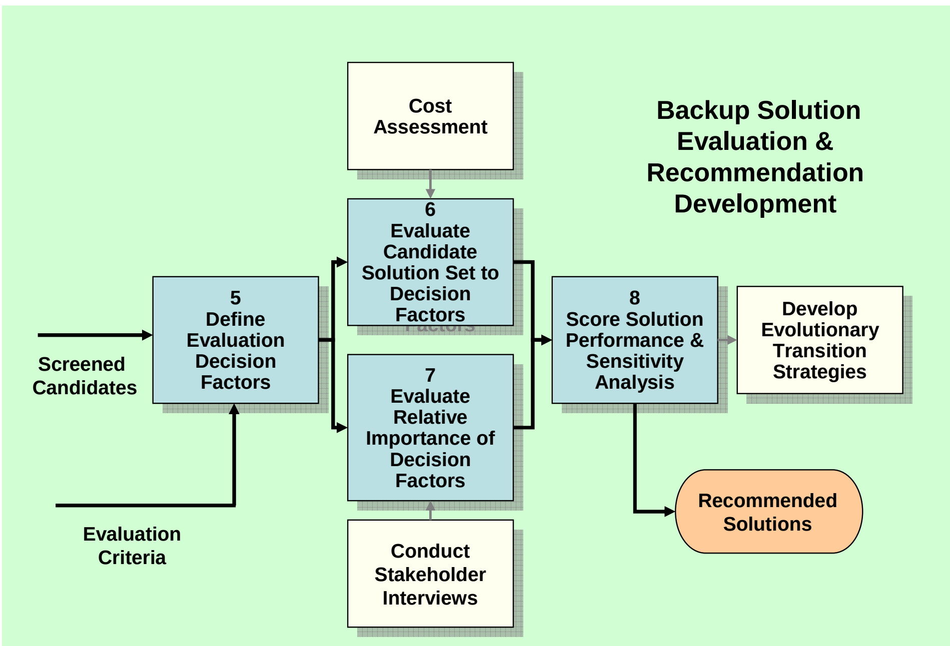

Figure 6-1: SatNav Backup Evaluation Process

The identification of evaluation decision factors was primarily addressed in Section 3, which derives the evaluation criteria for this study. The applied evaluation decision factors considered in this section are those criteria defined in Section 3 less the threshold criteria applied for candidate screening in Section 4. For this subtask, no further elaboration of approach is needed. For the other major task activities noted above, details to how these steps were implemented are the topics of the following subsections.

6.1.1 Approach for Assessment of Backup Solutions to Evaluation Factors

This step in the AHP included the relative comparison of candidate SatNav backup solutions within the context of individual evaluation factors. The lower level process applied to perform this work is shown in Figure 6-2.

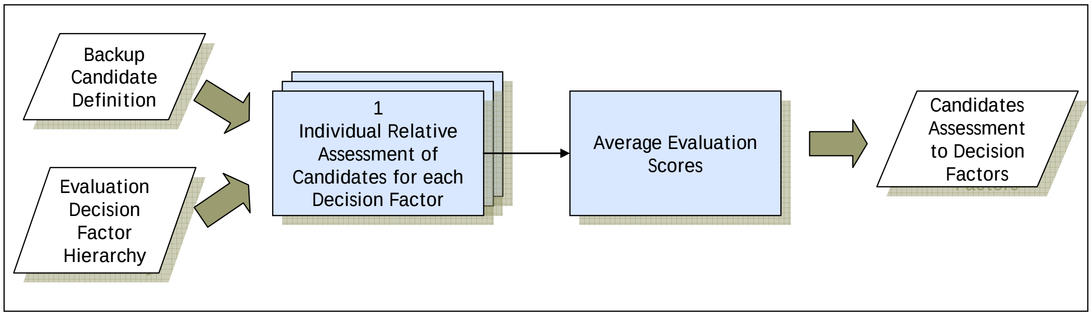

Figure 6-2: Workflow Diagram for Assessment of Backup Solutions to Evaluation Factors

The figure above reveals that one input to this task was a common understanding of the candidate solution, where the backup candidate definition (which identified the functional solution elements of the ground and avionics infrastructure and the overall capability of solution) was used (as defined in Section 4). A second input was the evaluation decision factor hierarchy, which captured the decision factors that the candidates were evaluated against.

The first step to evaluate candidate solutions to evaluation factors was relative assessment of solutions specific to individual evaluation factors, as performed by individual study team participants. To apply this process, an assessment scale was defined, as shown in Table 6-1.

Table 6-1: Evaluation Scale

Scoring (Rating)	Value	Description
Excellent	1	Exceeds the requirement or superior to other candidates
Satisfactory	0.8	Meets requirements but another candidate exceeds
Marginal	0.5	Only meets some requirements and other candidates does better
Unsatisfactory	0.01	Inferior to other choices or fails to meet requirements

Note: Any value between 0.01 and 1 can be assigned

Using this scale, an assessment table was generated where an individual evaluator would rate the candidate solution against each of the evaluation decision factors relative to other candidates. A sample implementation of this table is shown in Table 6-2. A similar table was generated for each of the SatNav backup solution candidates by each evaluator.

Table 6-2: Backup Candidate Assessment Table

Decision Factor	Rating	Justification/Comments
Life Cycle Costs	[to be completed by evaluator]	[to be completed by evaluator]
Long Term Flexibility	[to be completed by evaluator]	[to be completed by evaluator]
Redundant & Seamless	[to be completed by evaluator]	[to be completed by evaluator]
Early Avionics Available	[to be completed by evaluator]	[to be completed by evaluator]
Global Harmonization	[to be completed by evaluator]	[to be completed by evaluator]
Spectral Efficiency	[to be completed by evaluator]	[to be completed by evaluator]
Infrastructure Protection	[to be completed by evaluator]	[to be completed by evaluator]

The next step in the process of evaluation candidate solutions was to average the evaluation scores to arrive at a single assessment score for each candidate solutions. This process accommodated the influence of differing perspectives of how candidates perform with regard to individual evaluation factors in the scoring process. The product of this work was an assessment table (as shown above) for each candidate backup solution that was carried further in the AHP analysis.

6.1.2 Approach for Weighting Evaluation Decision Factors

Another step in the final evaluation of candidate solutions was the weighting of decision factors. When different candidate solutions are assessed against individual evaluation factors, there may be some candidate that score well with regard to one decision factor (for example, decision factor A), while scoring poorly with regard to a second decision factor (decision factor B). At the same time, other candidate solutions may perform in an opposite manner, scoring well with regard to decision factor B, but poorly with regard to decision factor A. To help with the interpretation of scoring results, an understanding of the relative importance of weighting factors is needed.

The AHP includes a step to address this need and this is a key step for incorporating stakeholder input into the Analytical Hierarchy Process. To capture stakeholder inputs, all decision factors were compared pair-wise through a survey of stakeholders. Stakeholders were asked “Is decision factor X very strongly/strongly/moderately or equally more/less important to decision factor Y” for all combinations of decision factors. An excerpt of the table used to capture survey results is shown in Figure 6-3. Although shown in tabular format, all of the surveys were conducted verbally, providing the assessment team to provide appropriate background and elaboration of decision factor definitions. The full survey format and information made available to survey participants is shown in Appendix E.

ID	Decision Factor A		Relative Magnitude	Relationship Sense	Decision Factor B
1	Life cycle cost	is	○ Very Strongly ○ Strongly ○ Moderately ○ Equally	○ More important than ○ Less important than ○ [equally] important to	Long term flexibility
2	Life cycle cost	Is	○ Very Strongly ○ Strongly ○ Moderately ○ Equally	○ More important than ○ Less important than ○ [equally] important to	Redundant & seamless operation
3	Life cycle cost	Is	○ Very Strongly ○ Strongly ○ Moderately ○ Equally	○ More important than ○ Less important than ○ [equally] important to	Early avionics available

Figure 6-3: Excerpt of Stakeholder Survey Comparing Decision Factors Pair-Wise

Applying the methodology of the AHP, results of the pair-wise survey of decision factors were used to populate a pair-wise comparison matrix. In this matrix, numerical scores were applied to survey results. Specific values included:

- Very strongly more important than: 7
- Strongly more important than: 5
- Moderately more important than: 3
- Equally important to: 1
- Moderately less important than: 1/3
- Strongly less important than: 1/5
- Very strongly less important than: 1/7

An example application of these values to a pair-wise comparison of survey results is shown in Figure 6-4. Note that in the figure below, the decision factors in the column can be considered “decision factor X” and those in the row across the top can be considered “decision factor Y” when applying the statement “decision factor X is very strongly/strongly/moderately or equally more/less important to decision factor Y”.

Scale:	
1 - equally important	
3 - moderate more important	1/3 - moderately less important
5 - strongly more important	1/5 - strongly less important
7 - very strongly more important	1/7 - very strongly less important

Is [row] more important than [column]? (>1)	Low Life Cycle Cost	Redundant Capability and Minimal Operational Impact	Long Term Flexibility	Early Avionics Availability	Global Harmonization	Spectral Efficiency	Additional Key Infrastructure Protection
Low Life Cycle Cost		7	7	7	7	7	7
Redundant Capability and Minimal Operational Impact	0.1429		1	1	1	0.143	3
Long Term Flexibility	0.1429	1		3	5	7	1
Early Avionics Availability	0.1429	1	0.333		3	1	3
Global Harmonization	0.1429	1	0.2	0.333		0.333	0.333
Spectral Efficiency	0.1429	7	0.143	1	3		1
Additional Key Infrastructure Protection	0.1429	0.3333	1	0.333	3	1	

Figure 6-4: AHP Comparison Matrix of Pair-Wise Survey Results

The comparison matrix above can be generated to reflect a single stakeholder survey response, or averaged for a set of stakeholders or across stakeholder sets. To calculate averaged results, the geometric mean of each individual comparison score was computed.

The final part of this AHP evaluation step was the calculation of decision factor weights using the pair-wise comparison results. This step required matrix mathematics including determining the eigenvalues of the matrix, determining the eigenvector corresponding to the largest eigenvalue, and then normalizing the resulting eigenvector. An example of the calculations performed using the sample matrix above is provided in Figure 6-5. Note that in this example, decision factors are identified by number (e.g. corresponding to the matrix above, decision factor 1 is “low life cycle cost”, decision factor 2 is “redundant capability and minimal operational impact”, etc).

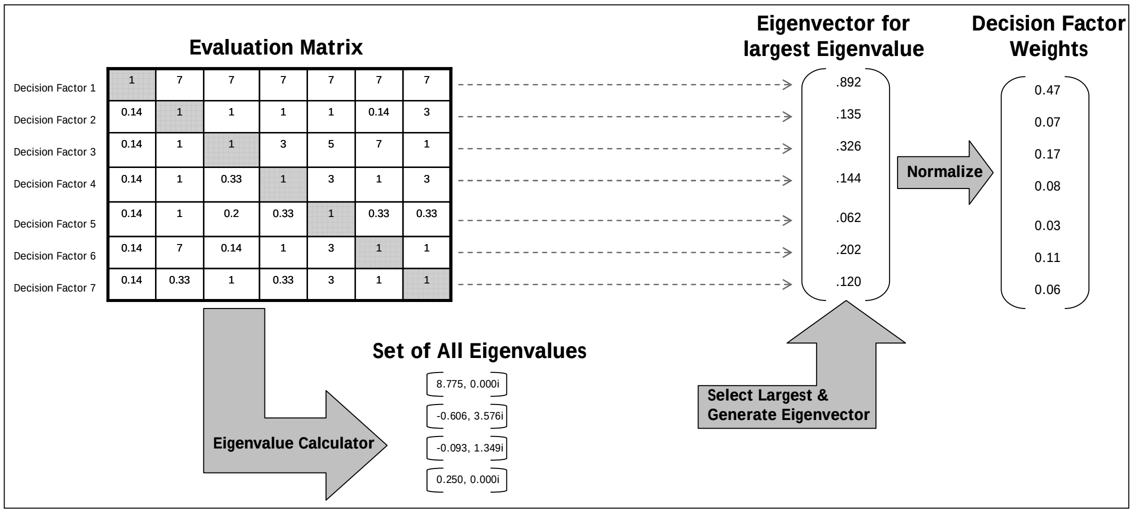

Figure 6-5: AHP Matrix Calculations to Determine Decision Factor Weights

Applying the process described above resulted in a set of decision factor weights ranging from zero to 1 where the sum of all weights equals 1. A sample set of decision factor weights, corresponding to the example provided above, is shown in Table 6-3.

Table 6-3: Example Decision Factor Weights

Decision Factor	Weight
Decision Factor 1	0.47
Decision Factor 2	0.07
Decision Factor 3	0.17
Decision Factor 4	0.08
Decision Factor 5	0.03
Decision Factor 6	0.11
Decision Factor 7	0.06

6.1.3 Approach for Calculating Overall Solution Priority

Upon completion of the evaluation of candidate solutions to decision factors and development of decision factor weights, the two products can be combined to calculate the overall solution priority rating. For each evaluation decision factor, the evaluation rating result is multiplied with the decision factor rating, and the results are summed across all decision factors. The resulting solution priorities range from 0 to 1. A sample calculation of a solution priority is shown in Figure 6-6.

	Solution under Evaluation:	DME/DME/INS		Average
				TRUE
Selected Ranking Perspective:		US_AirCarrier		

	Backup Solution Scoring			
Decision Factor		Evaluation Score	Weight	Overall SCORE
	Life Cycle Costs	☑ 0.40	16.48%	0.065928659
	Long Term Flexibility	☑ 0.55	20.46%	0.112525625
	Redundant & Seamless	☑ 0.78	19.31%	0.149661747
	Early Avionics Available	☑ 0.93	5.37%	0.049682247
	Global Harmonization	☑ 0.88	20.71%	0.181170562
	Spectral Efficiency	☑ 0.55	10.17%	0.055924559
	Infrastructure Protection	☑ 0.26	7.50%	0.019132841
			TOTAL	0.63402624

Figure 6-6: Sample Calculation of Backup Solution Priority

Using the calculator tool developed for this assessment, priority calculations were computed for each of the candidate backup solutions.

6.1.4 Sensitivity Analysis Approach

The final step of the AHP was to perform a sensitivity analysis. In this assessment, this was performed in two ways. First, decision factor weighting results and corresponding overall solution priority calculation results were calculated for various stakeholder sets. Specifically, the collected surveys were organized into the following sets to support sensitivity analysis:

- US – Air Carrier
- US – General Aviation
- US – Government and Standards Organizations
- Europe – Air Carrier
- Europe – General Aviation
- Europe – Government and Standards Organizations
- All US
- All Europe
- All Air Carrier
- All General Aviation
- All Government and Standards Organizations
- All Stakeholders

Assessment results were shown specific to these defined sets of stakeholders.

In addition to sensitivity based on stakeholder weighting of decision factors, evaluation results were also considered with regard to impact of specific evaluation decision factors. Results were generated for the

case where all decision factors were accounted for as well as specific cases when one of the decision factors did not factor into the evaluation results. Sensitivity to individual decision factors was performed by analysis of the following cases:

- All decision factors accounted for
- Evaluation without life cycle cost decision factor
- Evaluation without infrastructure protection decision factor

Assessment results are shown specific to these defined cases. Results of the application of the methodology described above are included in the subsequent sections of this report.

6.2 EVALUATION FACTORS REVIEW

Before presentation of evaluation results, it is instructive to review the evaluation decision factors that were applied to perform candidate SatNav backup solution assessments. A full set of evaluation criteria was introduced in Section 3, which describes the motivation and traceability of the criteria. In Section 4.2, a subset of these criteria were identified as threshold criteria and used to perform a screening of alternatives to identify to applicable candidate backup solutions. The remaining evaluation criteria then became the decision factors used for further assessment and comparison of candidate solutions. As introduced in Section 3.4.3, the same decision factors represent a set of evaluation considerations (organized in hierarchical fashion) (reference Section 3 for further detail/definition of evaluation criteria) Here, the top-level evaluation decision factors are simply restated in Table 6-4 with their corresponding high-level definition.

Table 6-4: Review of Evaluation Decision Factors

	Decision Factor	Definition
1	Low Life Cycle Costs	This factor values low life cycle costs to the users and the infrastructure provider to provide and maintain a SatNav backup system
2	Long Term Flexibility	This factor values that the solution should be flexible in adapting to changing needs without significant reinvestments. For example, the SatNav backup should easily accommodate evolutionary changes to the performance based navigation requirements. Such requirements, driven by increases in traffic density and decreases in separation distances, could be introduced with minimal additional cost to both infrastructure support and users. Support for non precision approaches could be added to airports without major redesign or expansion of ground aid systems.
3	Redundant Capability and minimal Operational Impact (also referred to as Redundant and Seamless)	This factor values the navigation capability of the backup that enables near equivalent navigation performance as with the primary Satellite Navigation, and also that when required, the transition to the backup is seamless, with no exceptional crew or ground actions required

	Decision Factor	Definition
4	Early Avionics Availability	This factor values the early availability of avionics for the SatNav backup. We assume that other backup solutions using traditional navigation aids would support the needs of users until the proposed backup avionics are available.
5	Global Harmonization	This factor values the support of a defined SatNav backup beyond only the US or Europe. Full global harmonization requires international standards. Participating regions must commit to necessary investments to build and operate required ground aids
6	Spectral Efficiency	This factor values the efficient use of aeronautical radio spectrum, allocation of scarce resources to important future aviation voice and data needs.
7	Additional Key Infrastructure Protection (also referred to as Key Infrastructure Protection)	This factor values that the SatNav backup system would also benefit other key aviation and national infrastructure Position, Navigation, and Timing (PNT) requirements. (The distribution of precise timing information is critical to sustaining many requirements including future aviation data link communications, ADS-B, and the whole national telecommunications infrastructure.)

6.3 EVALUATION OF BACKUP SOLUTIONS TO EVALUATION FACTORS

As described in Section 6.1.1, the evaluation of candidate backup solutions to evaluation decision factors was made to determine the relative performance of candidate solutions. The evaluation of candidate solutions to each decision factor, performed by the assessment team, was made by applying evaluation scores as follows:

- Excellent (exceeds the requirement or superior to other candidates): value = 1
- Satisfactory (meets requirements but other candidates exceed): value = 0.8
- Marginal (only meets some requirements and other candidates do better: value = 0.5
- Unsatisfactory (inferior to other choices or fails to meet requirements): value = 0.01

The scores noted above provided guidance on how candidate solutions could be scored; in practice, any values between 0.01 and 1 can be used to score a candidate backup solution to individual decision factors. Performing individual evaluation assessments and then applying a consensus building process, a set of evaluation scores to be applied in the candidate backup solution AHP assessment were calculated.

For the DME/DME/INS Solution, evaluation scores are captured in Table 6-5. This candidate has the highest scores with regard to Early Avionics Ability and Global Harmonization. With regard to avionics, equipment is currently available. In terms of harmonization, both the US and Europe both have extensive DME networks in place, providing potential to implement a harmonized solution. This candidate performs poorly with regard to Additional Key Infrastructure Protection as there is some applicability of DME outside of the backup capability, but this is limited and specific to navigation.

Table 6-5: Evaluation of DME/DME/INS Solution to Decision Factors (Relative Assessment)

	Decision Factor	Rating	Justification/Evaluation Notes
1	Low Life Cycle Costs	0.4	D/D/I has the highest relative cost (overall) compared to other solutions; but is a low cost alternative for at least one stakeholder
2	Long Term Flexibility	0.55	DME will require additional infrastructure as coverage needs change; D/D/I coverage: difficult to support RNP 1.0 and marginally possible for RNP-0.3
3	Redundant Capability and Minimal Operational Impact	0.775	D/D/I can meet all air space requirements except possibly RNP-0.3 and below.
4	Early Avionics Availability	0.925	D/D/I is currently available to provide backup.
5	Global Harmonization	0.875	US and Europe both have extensive operational DME networks and both are considering D/D/I as a candidate backup solution
6	Spectral Efficiency	0.55	DME is a significantly higher spectrum consumer than other candidates.
7	Additional Key Infrastructure Protection	0.255	Limited application.

For the GNSS/INS Solution, evaluation scores are captured in Table 6-6. This candidate has the highest scores with regard to Spectral Efficiency, Early Avionics Availability, and Low Life Cycle Costs. The high rating with regard to spectral efficiency results from minimal to no spectrum requirements outside of GNSS. For this solution, avionics for most users are available today and manufacturers indicate progress on developing smaller/lighter weight implementations. This was overall the relative best cost performer and for some stakeholders, the best cost performer. This candidate performs poorly with regard to Additional Key Infrastructure Protection as there is minimal infrastructure benefit associated with this solution other than nominal help from the inertial to assist with surveillance position determination and possible application to other transportation segments.

Table 6-6: Evaluation of GNSS/INS Solution to Decision Factors (Relative Assessment)

	Decision Factor	Rating	Justification/Evaluation Notes
1	Low Life Cycle Costs	0.8	GNSS/INS has the lowest relative cost (overall) compared to other solutions
2	Long Term Flexibility	0.5525	GNSS/INS is flexible as long as the assumption of local GPS outages applies. For an entire system outage, GNSS/INS is not an applicable solution.
3	Redundant Capability and minimal Operational Impact	0.55	GNSS/INS meets all air space requirements but has time limited coasting capability.
4	Early Avionics Availability	0.8	Some GNSS/INS retrofit may be needed. Study assumes need for ground position update.
5	Global Harmonization	0.65	US and Europe are currently considering GNSS/INS as a backup candidate. Current GNSS/INS equipage is limited to larger aircraft classes.

	Decision Factor	Rating	Justification/Evaluation Notes
6	Spectral Efficiency	0.9	GNSS is already available and has no other implication on spectrum utilization. Added position update capability would be very local and minimal power.
7	Additional Key Infrastructure Protection	0.14	Limited application. Some assist to surveillance position determination and other transportation.

For the eLORAN Solution applied evaluation scores are captured in Table 6-7. This candidate has the highest scores with regard to Spectral Efficiency and Key Infrastructure Protection. With regard to spectrum, the candidate rates high as the system operates using a small spectrum band. The high rating with regard to key infrastructure protection results from the fact that its implementation would provide additional capability/roles, such as timing. This candidate performs poorly with regard to Global Harmonization as there are no international standards available and there exists only a limited consideration of eLORAN as a candidate SatNav backup solution on an international level.

Table 6-7: Evaluation of eLORAN Solution to Decision Factors (Relative Assessment)

	Decision Factor	Rating	Justification/Evaluation Notes
1	Low Life Cycle Costs	0.7	In terms of overall relative cost performance, this candidate is one of the better solutions; however, it does require investment cost for all sets of stakeholders.
2	Long Term Flexibility	0.85	Can satisfy RNP-0.3 for all procedures. Once implemented, flexible to accommodate changing needs with best CONUS coverage.
3	Redundant Capability and minimal Operational Impact	0.85	eLORAN meets projected performance requirements to the primary means and provides a seamless transition to backup once fully implemented. While eLORAN is capable of RNP-0.3, it does not exceed this requirement.
4	Early Avionics Availability	0.525	With concerted US effort, standards could be developed and equipage available by 2020 and assumed certain by 2025.
5	Global Harmonization	0.1025	Global standards and equipment for eLORAN to support flight operations does not substantially exist. eLORAN has no current equipage and international standards need to be developed. There is some maritime and state PNT interest in Europe for a modernized LORAN however. LORAN stations would need to be added in other areas such as S. America for global coverage. It however does not seem to be cost prohibitive to add stations.
6	Spectral Efficiency	0.9125	eLORAN operates in a narrow spectrum band.
7	Additional Key Infrastructure Protection	0.875	eLORAN has the capability to protect the infrastructure more than the other candidates and offers additional capability (e.g. timing capability)

A summary of results for the relative assessment of candidate backup solutions for the evaluation decision factors is provided in Table 6-8.

Table 6-8: Summary of Relative Assessment of Candidates to Decision Factors

	Decision Factor	DME/DME/INS	GNSS/INS	eLORAN
1	Low Life Cycle Costs	0.4	0.8	0.7
2	Long Term Flexibility	0.55	0.5525	0.85
3	Redundant Capability and minimal Operational Impact	0.775	0.55	0.85
4	Early Avionics Availability	0.925	0.8	0.525
5	Global Harmonization	0.875	0.65	0.1025
6	Spectral Efficiency	0.55	0.9	0.9125
7	Additional Key Infrastructure Protection	0.255	0.14	0.875

Another view of the evaluation results is provided in Figure 6-7 below. This provides a visual view of which candidates perform better with regard to individual evaluation decision factors. Note that all candidates are the best performer with regard to at least one decision factor, but no one candidate performs clearly better or worst across the board.

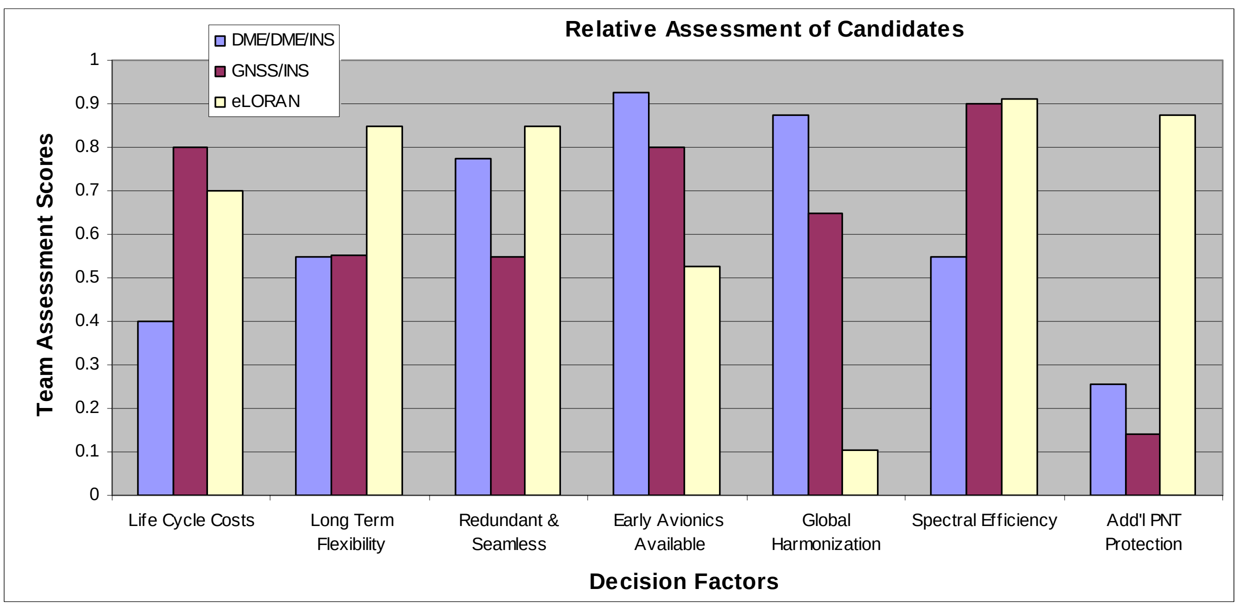

Figure 6-7: Relative Assessment of Candidate Solutions to Decision Factors

In the relative assessment of the candidates,

- eLORAN had relatively higher assessment for 'Long Term Flexibility'. The expected difficulty and cost in expanding DME station coverage to meet high terminal area RNP requirements was a concern.

- eLORAN and DME/DME/INS had high assessment for the 'Redundant and Seamless' failover decision factor. Here, GNSS/INSS scored lower due to potential GNSS disruption scenarios that would be more widespread than the specific terminal disruption case studied in this report.
- eLORAN scored lowest for 'Global Harmonization' where DME/DME/INS scored the highest.
- Both GNSS/INS and DME/DME/INS scored better than eLORAN for preference for 'Early Avionics Equipage'.
- DME/DME/INS was considered a high consumer of the frequency spectrum and scored lowest for 'Spectral Efficiency'.
- eLORAN and its potential to provide 'Additional PNT Protection' was recognized.

6.4 WEIGHTING OF EVALUATION FACTORS – STAKEHOLDER SURVEYS

A significant part of the process applied to evaluate candidate backup solutions was gathering stakeholder inputs and applying them in the context of solution evaluation. As noted previously, two sets of stakeholder interviews were conducted. The first set helped to shape the overall set of candidate solutions for consideration as well as the evaluation criteria to be applied in this assessment. In the second set of interviews, stakeholders were surveyed to gain their perspective on the relative importance of the defined set of evaluation factors. To support this effort, a variety of stakeholders were interviewed. A list of these stakeholders is provided in Table 6-9. The Notes indicate how aircraft builders and avionics manufacturers were grouped into the stakeholder sets.

Table 6-9: Stakeholders Interview Supporting Weighting of Evaluation Decision Factors

Basic Stakeholder Sets	Notes
US – Air Carrier	Includes large airframe builders and avionics manufactures for this segment
US – General Aviation	Includes avionics manufactures for this segment
US – Government & Standardization Organizations	
Europe – Air Carrier	Includes large airframe builders and avionics manufactures for this segment
Europe – General Aviation	Includes airframe builders for this segment
Europe – Government & Standardization Organizations	

As noted in Section 6.1.2, participants with the stakeholder sets were interviewed to obtain their assessment of the relative importance of the evaluation decision factors applied for assessment of SatNav backup solutions. This survey, provided in full in Appendix E, includes a pair-wise comparison of all evaluation decision factors. The survey participant was asked "Is decision factor X very strongly/strongly/moderately or equally more/less important to decision factor Y" for all combinations of decision factors. The results of the pair-wise comparison of decision factors wais used to populate the

AHP pair-wise comparison matrix with a numerical score associated with the survey input, defined as follows:

- Very strongly more important than: 7
- Strongly more important than: 5
- Moderately more important than: 3
- Equally important to: 1
- Moderately less important than: 1/3
- Strongly less important than: 1/5
- Very strongly less important than: 1/7

An example of the translation of a survey response to a pair-wise comparison matrix input is shown in Figure 6-8. Here, a survey respondent indicates that the first decision factor (Global Harmonization) is moderately more important than the second decision factor (Long Term Flexibility). (Note this also implies the converse, specifically, Long Term Flexibility is moderately less important than Global Harmonization).

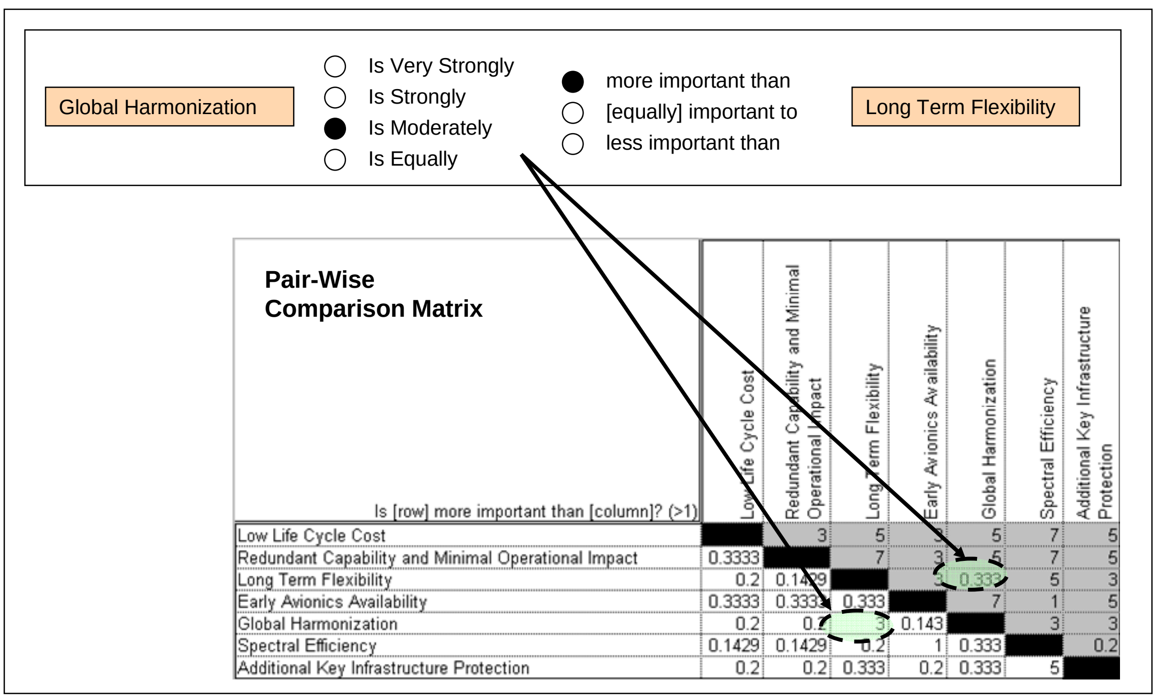

Figure 6-8: Translating Survey Results into a Pair-Wise Survey Result Matrix

Survey results were captured for each stakeholder individually and then combined into stakeholder sets to be applied in the analysis. A total of twelve sets of results were captured. For each, the relative

importance of the decision factors, identified as decision factor weights were calculated. A summary of the weighting results is provided in Table 6-10.

Table 6-10: Summary of Decision Factor Weighting Results

Decision Factor	Total	U.S.				Europe				Combined (US/Europe)		
		All	**AC**	**GA**	**Gov't/ Stnds**	**All**	**AC**	**GA**	**Gov't/ Stnds**	**AC**	**GA**	**Gov't/ Stnds**
Life Cycle Cost	.11	.097	.15	.06	.08	.11	.165	.08	.11	.16	.07	.097
Redundant & Seamless	**.197**	**.20**	.192	**.31**	.16	.19	.17	.11	.22	.18	**.24**	.195
Long Term Flexibility	.14	.16	**.195**	.15	.13	.12	.10	.20	.12	.15	.18	.13
Early Avionics Availability	.09	.10	.06	.18	.098	.07	.12	.04	.06	.08	.13	.08
Global Harmonization	.17	.12	**.195**	.07	.11	**.25**	**.23**	.23	**.24**	**.22**	.12	.16
Spectral Efficiency	.18	.17	.12	.09	**.22**	.18	.12	**.28**	.18	.12	.15	**.21**
Infrastructure Protection	.12	.15	.09	.13	.199	.07	.095	.05	.07	.09	.11	.13

The table above includes shading to indicate the decision factor that was assigned the highest priority based on stakeholder inputs. Please note that in general, four factors were defined to be of greatest importance to stakeholders. These included the following:

- Redundant Operations and Seamless Failover
- Global Harmonization
- Spectral Efficiency
- Long Term Flexibility

Additional insight into stakeholder perception of the importance of decision factors can be gain through review of the results using visual representation of results. Figure 6-9 provides the results for the Air Carrier stakeholder representatives. Although results slightly differ between US and Europe representatives in this group that were surveyed, overall, the results indicate that Global Harmonization is a very important decision factor for this set of users.

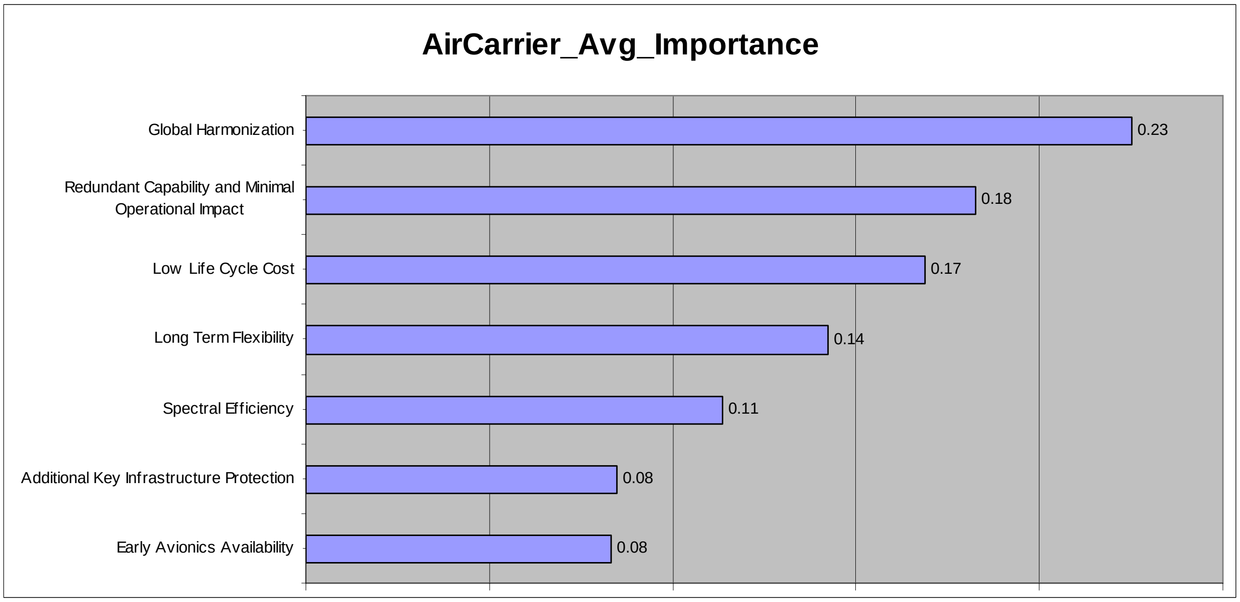

Figure 6-9: Air Carrier Decision Factor Weights

For General Aviation, the criteria weighting results are shown in Figure 6-10. For this group of users, redundant capability and seamless failover was noted as the most important factor to consider when assessing backup solutions. This is slightly more important than long term flexibility and spectral efficiency, as assessed by this set of stakeholders.

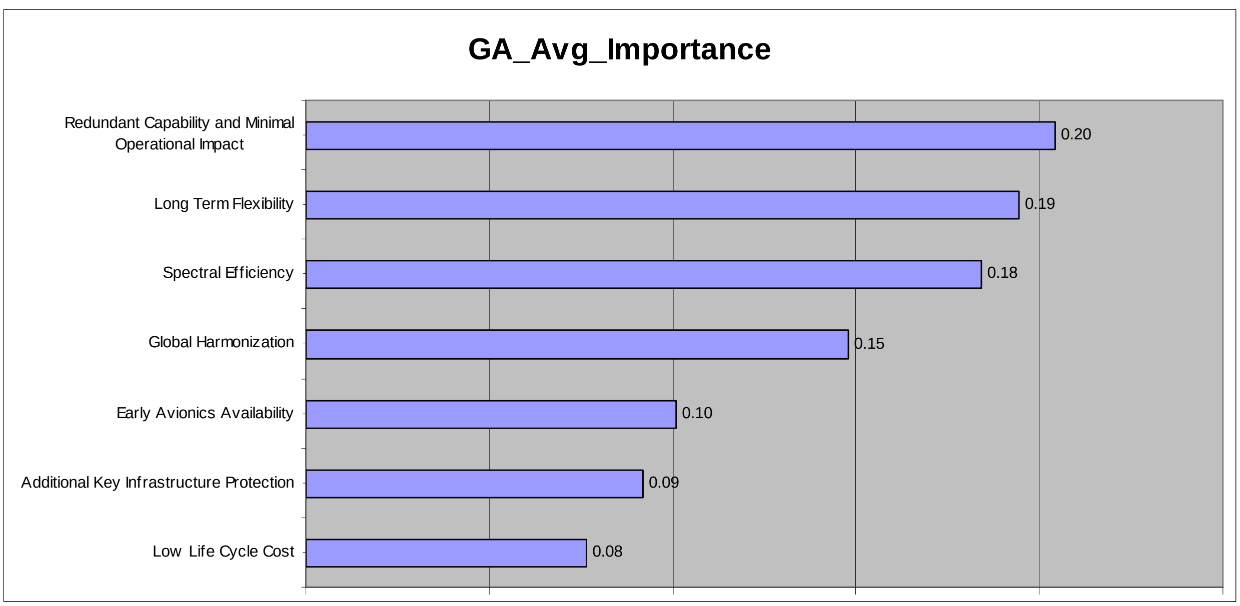

Figure 6-10: General Aviation Decision Factor Weights

For government and standards organizations, the weighting of decision factors is shown in Figure 6-11. Survey responses from this set of stakeholders indicate that spectral efficiency and redundant capability and seamless failover are the most important decision factors.

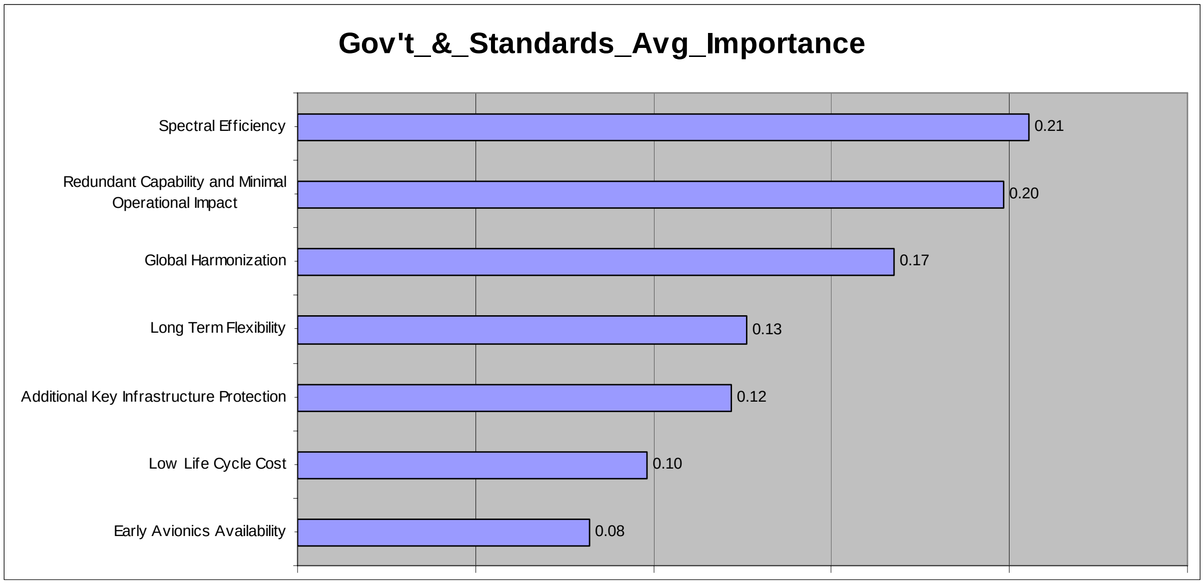

Figure 6-11: Government and Standards Organization Decision Factor Weighting

Finally, the overall weighting results, which account for all surveyed stakeholders is provided in Figure 6-12. Considering the full set of survey results, the evaluation decision factor assigned the highest importance was redundant capability and seamless failover. This was followed by global harmonization and spectrum efficiency. Note that these decision factors are the same three that score the highest for at least one set of the stakeholders.

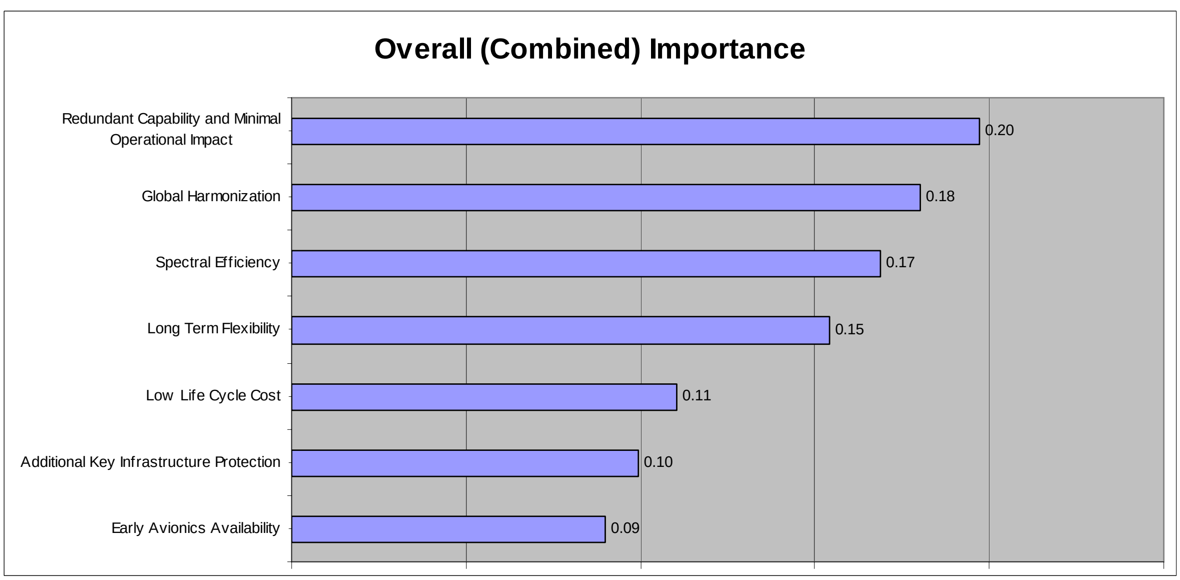

Figure 6-12: Overall (Combined) Decision Factor Weighting

The results provided above were used to interpret the evaluation results computed in Section 6.3. By combining the evaluation scores with weighting solutions, a prioritization of backup solutions can be defined. This prioritization can be computed considering the full range of stakeholders interviewed, or can be specific to individual stakeholder groups.

6.5 ASSESSMENT OF BACKUP SOLUTION PREFERENCES AND SENSITIVITY ANALYSIS

The assessment of the candidate backup solution priorities resulted from the combination of the relative assessment of candidate backup solutions to the decision factors and the weighting of decision factors. As described in Section 6.1.3, an evaluation scoring table was used to compute the individual score of a technology specific to the stakeholder evaluations of decision factor importance. This process can be repeated to examine the sensitivity of results to specific stakeholder sets as well as sensitivity to specific evaluation factors.

A summary of key results is provided in Table 6-11. This table identifies the applied weights and associated weighted scores for the candidate solutions for the Air Carrier (All AC); General Aviation (GA); Government & Standards Organizations (Gov/Stnds); and Combined stakeholder categories.

Table 6-11: Assessment Results – Solution Preference for Key Stakeholder (Sets)

Evaluation Criteria/Decision Factors	Stakeholder Weighting				Evaluator Scoring		
	All AC	**All GA**	**All Gov/Stnds**	**All**	**D/D/I**	**GNSS/INS**	**eLORAN**
Life Cycle Costs	.16	.07	.097	.11	.4	.8	.7
Redundant & Seamless Failover	.18	.24	.195	.197	0.55	0.5525	0.85
Long Term Flexibility	.16	.18	.13	.14	0.775	0.55	0.85
Avionics Availability	.08	.13	.08	.09	0.925	0.8	0.525
Global Harmonization	.22	.12	.16	.17	0.875	0.65	0.1025
Spectrum Efficiency	.12	.15	.21	.18	0.55	0.9	0.9125
Key Infrastructure Protection	.09	.11	.13	.12	0.255	0.14	0.875
Weighted Score – All AC					.645	.641	.638
Weighted Score – All GA					.643	.636	.709
Weighted Score – All Gov/Stnds					.629	.634	.699
Weighted Score – Overall					.641	.637	.682

Another view of the results is provided in Figure 6-13. The data indicates that for some stakeholders, the eLORAN solution is slightly preferable to the other candidates solutions, and there is very little distinction between the preference of GNSS/INS and DME/DME/INS solutions. Overall, the candidate performance is very close.

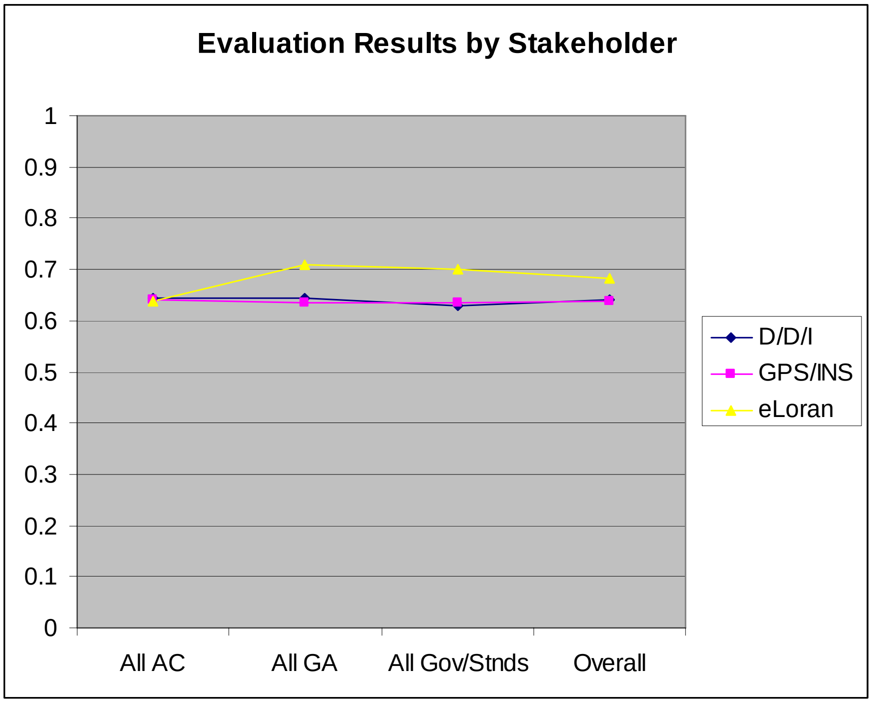

Figure 6-13: Assessment Results – Solution Preference (Key Stakeholder Sets)

The candidate solutions were evaluated to a wider set of stakeholder classifications, as introduced in Section 6.2.3, and the expanded set of results are provided in Table 6-12 and Figure 6-14 below. Note that in the table, candidate solution results with the highest preference score are highlighted. These additional data points provide insight into candidate preferences for sub-categories of users within the larger stakeholder sets addressed in Figure 6-13 above. These additional data points indicate similar preference results to those previously described. Specifically, eLORAN was identified as the most preferable candidate for the majority of the stakeholder sets; however the incremental preference over the other candidate solutions is small. For some of the stakeholders interviewed, the highest preference solution was GNSS/INS, but the incremental preference over DME/DME/INS is marginal.

Table 6-12: Assessment Results – Solution Preference for All Stakeholder Sets

	D/D/I	GNSS/INS	eLORAN
Weighted Score – Overall	0.641	0.637	0.682
Weighted Score – All AC	0.645	0.641	0.638
Weighted Score – All GA	0.643	0.636	0.709
Weighted Score – Gov/Stnds	0.629	0.634	0.699
Weighted Score – Total US	0.627	0.608	0.721
Weighted Score – US AC	0.636	0.631	0.661
Weighted Score – US GA	0.666	0.597	0.736
Weighted Score – US Gov/Stnds	0.589	0.601	0.74
Weighted Score – Total Europe	0.658	0.661	0.637
Weighted Score – Europe AC	0.655	0.648	0.625
Weighted Score – Europe GA	0.64	0.683	0.671
Weighted Score – Europe Gov/Stnds	0.665	0.652	0.647

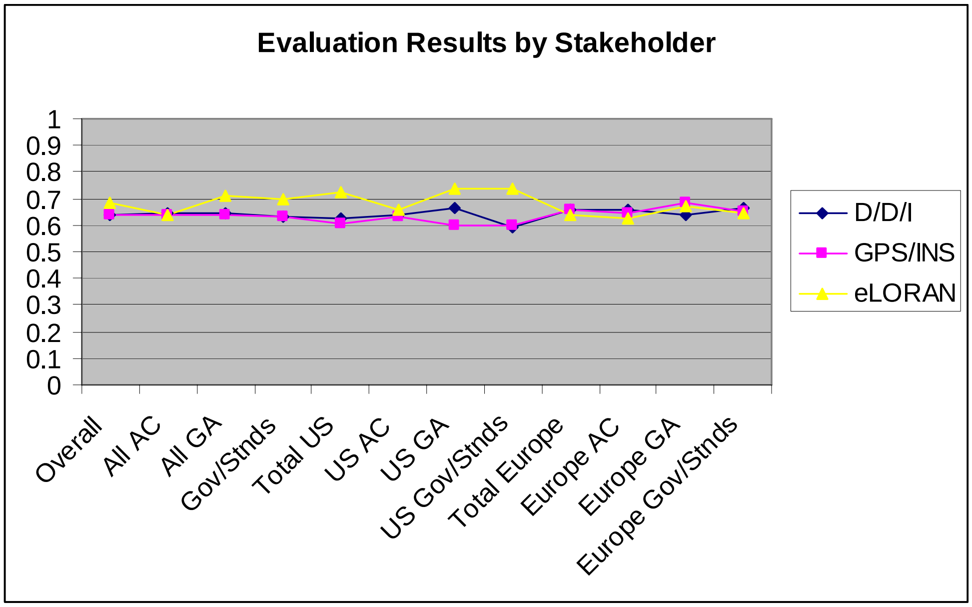

Figure 6-14: Assessment Results – Solution Preference (All Stakeholder Sets)

The results above are influenced by the performance of the candidate solutions to those decision factors that have been weighted of greatest importance by the stakeholders. The candidates that score well with regard to two or more of these factors (redundant operations and seamless failover, long term flexibility, global harmonization, and spectral efficiency) perform well in the overall weighted scores.

In addition to consideration of data with respect to individual stakeholder sets, evaluation results were analyzed with regard to sensitivity to two of the decision factors, Cost and Key Infrastructure Protection. As shown in previous results (Section 6.4), both of these factors are ones in which the candidate solutions perform very differently for different groups of stakeholders. For cost, this is due to the current equipage of aircraft with regard to navigation systems (e.g. there are significant difference between Air Carrier and General Aviation in terms of DME and INS equipage). For key infrastructure protection, this is due to the additional services capabilities (not specifically related to providing a backup capability) these candidate solutions may offer. Consideration of results discounting these factors (individually) is provided below.

First, when the cost criterion is discounted and stakeholder importance of decision factors is computed with regard to the other factors, the results as shown in Table 6-13 are found.

Table 6-13: Stakeholder Weighting of Decision Factors (Discounting the Cost Factor)

Decision Factor	Total	U.S.				Europe				Combined (US/Europe)		
		All	AC	GA	Gov't/ Stnds	All	AC	GA	Gov't/ Stnds	AC	GA	Gov't/ Stnds
Life Cycle Cost	0	0	0	0	0	0	0	0	0	0	0	0
Redundant & Seamless	**.22**	**.26**	.25	**.36**	.17	.19	.20	.12	**.26**	.22	**.22**	.22
Long Term Flexibility	.17	.19	**.25**	.16	.14	.15	.12	.20	.14	.18	.21	.14
Early Avionics Availability	.11	.12	.07	.19	.11	.09	.17	.05	.07	.11	.12	.09
Global Harmonization	.19	.13	.22	.06	.13	**.28**	**.28**	.28	.24	**.26**	.15	.18
Spectral Efficiency	.19	.16	.13	.10	**.24**	.22	.14	**.34**	.20	.14	.21	**.23**
Infrastructure Protection	.11	.15	.09	.13	.22	.07	.09	.009	.08	.09	.09	.14

Another view of the results, providing a visual representation of the data in the table above for the Air Carrier, General Aviation, Government & Standards and all combined stakeholder groups is provided in Figure 6-15 and Figure 6-16.

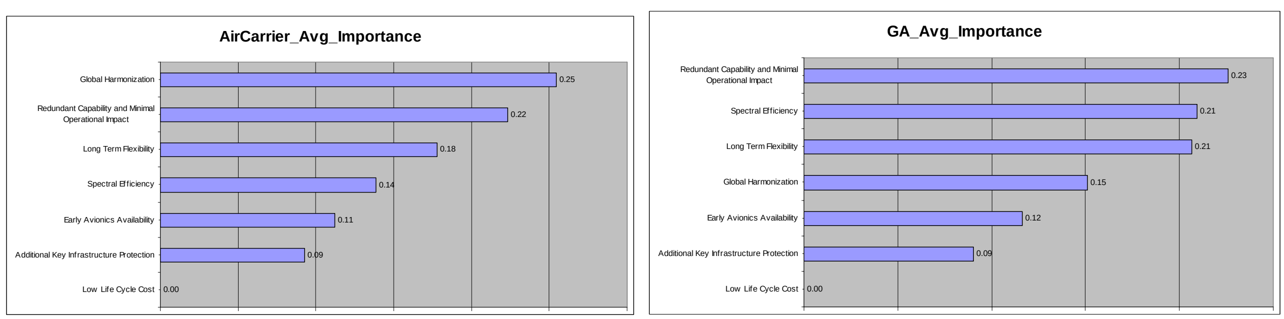

Figure 6-15: Air Carrier and GA Importance Weighting When Cost is not a Decision Factor

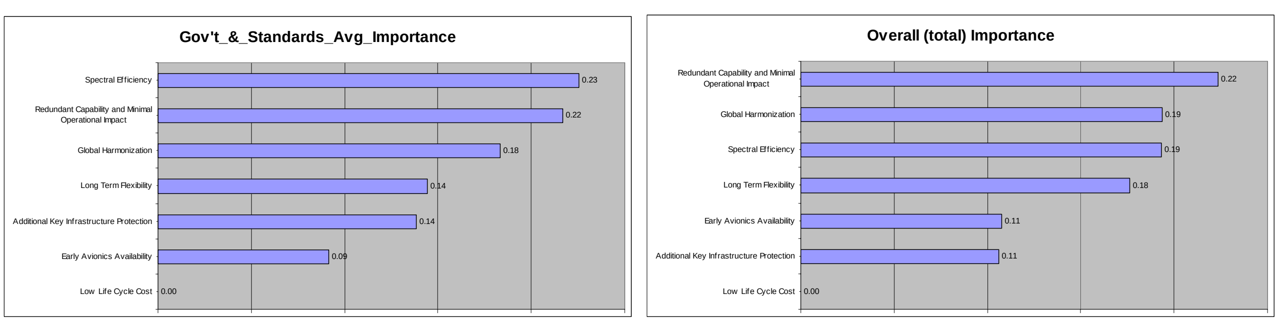

Figure 6-16: Gov/Stnds and Overall Combined Importance Weighting When Cost is not a Decision Factor

As in previous presentations of results, the tables above include shading to indicate the decision factor that was assigned the highest priority based on stakeholder inputs. Also, similar to the results considering all decision factors, the factors identified to be of greatest importance to stakeholders include:

- Redundant Operations & Seamless Failover
- Global Harmonization
- Spectral Efficiency
- Long Term Flexibility

Applying the adjusted weights above (discounting the cost decision factor), evaluation scores were recomputed as shown in Table 6-14 and Figure 6-17.

Table 6-14: Assessment Results – Solution Preference When Cost is Discounted

	D/D/I	GNSS/INS	eLORAN
Weighted Score – Overall	0.672	0.621	0.685
Weighted Score – All AC	0.697	0.614	0.634
Weighted Score – All GA	0.667	0.631	0.715
Weighted Score – Gov/Stnds	0.652	0.614	0.701
Weighted Score – Total US	0.651	0.589	0.73
Weighted Score – US AC	0.673	0.597	0.676
Weighted Score – US GA	0.686	0.588	0.749
Weighted Score – US Gov/Stnds	0.604	0.582	0.739
Weighted Score – Total Europe	0.694	0.647	0.629
Weighted Score – Europe AC	0.726	0.633	0.595
Weighted Score – Europe GA	0.683	0.708	0.648
Weighted Score – Europe Gov/Stnds	0.691	0.63	0.659

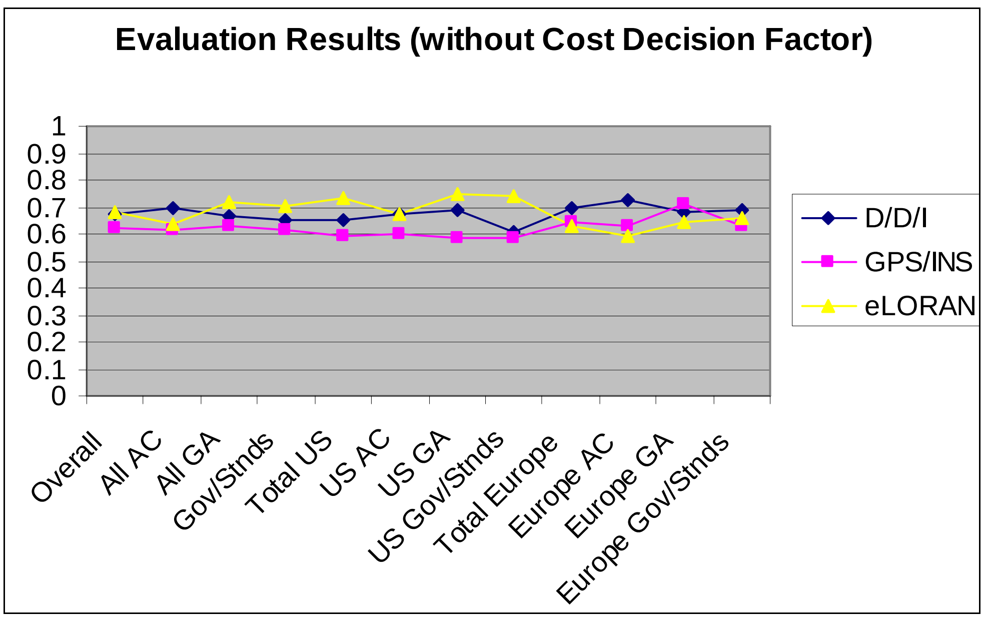

Figure 6-17: Assessment Results – Solution Preference (Cost Discounted)

In the results above, there is a slight adjustment in the candidate scores with the DME/DME/INS becoming a slightly preferable solution over GNSS/INS. For many stakeholders, eLORAN is the most preferable solution, but the preference over DME/DME/INS is marginal. Discounting the cost decision factor, the most preferable solution identified for each stakeholder set only changed in one case, where DME/DME/INS becomes the most preferable solution for the All Europe stakeholder category (passing over GNSS/INS by a slight margin).

A similar consideration of results is given to the scenario for when the Key Infrastructure Protection decision factor is discounted. In this case, the stakeholder importance of decision factors is computed with regard to the other factors with results as shown in Table 6-15.

Table 6-15: Stakeholder Weighting of Decision Factors (Discounting the Key Infrastructure Protection)

Decision Factor		U.S.				Europe				Combined (US/Europe)		
	Total	All	AC	GA	Gov't/ Stnds	All	AC	GA	Gov't/ Stnds	AC	GA	Gov't/ Stnds
Life Cycle Cost	.13	.12	.18	.08	.10	.13	.21	.08	.12	.20	.09	.11
Redundant & Seamless	**.22**	**.28**	.22	**.40**	.21	.16	.13	.11	.24	.18	**.23**	.23
Long Term Flexibility	.17	20	.20	.19	.16	.14	.10	.22	.13	.14	.23	.15
Early Avionics Availability	.10	.11	.06	.16	.11	.08	.14	.04	.07	.09	.10	.09
Global Harmonization	.20	.13	**.23**	.07	.14	**.27**	**.27**	.24	**.26**	**.26**	.15	.19
Spectral Efficiency	.19	.16	.11	.10	**.28**	.21	.15	**.30**	.19	.13	.21	**.24**
Infrastructure Protection	0	0	0	0	0	0	0	0	0	0	0	0

Another view of the results, providing a visual representation of the data in the table above for the Air Carrier, General Aviation, Government & Standards and all combined stakeholder groups is provided in Figure 6-18 and Figure 6-19.

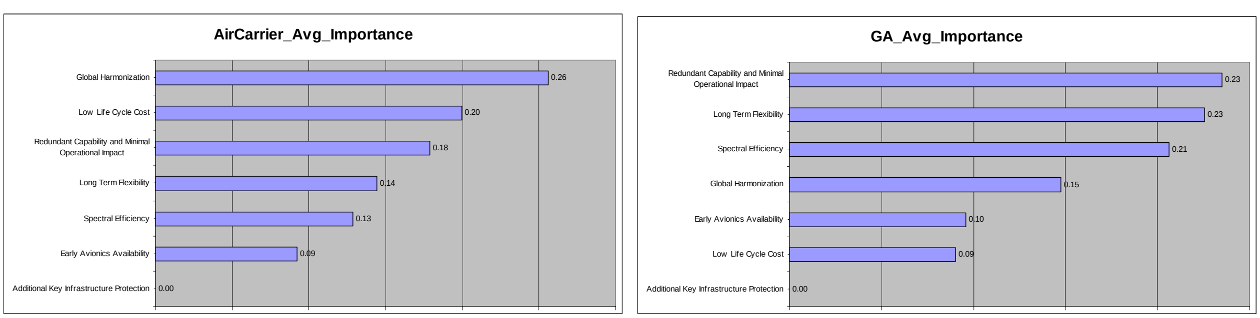

Figure 6-18: Air Carrier and GA Importance Weighting When Infrastructure Protection is Not a Decision Factor

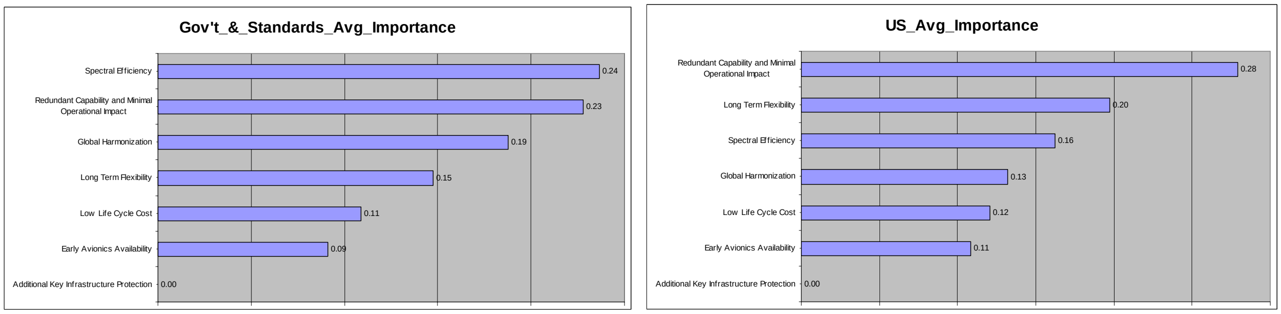

Figure 6-19: Gov/Stnds and Overall Combined Importance Weighting When Infrastructure Protection is not a Decision Factor

Once again, a similar set of decision factors is identified to be of greatest importance to stakeholders. These include:

- Redundant Operations & Seamless Failover
- Global Harmonization
- Spectral Efficiency

Applying the adjusted weights above (discounting the infrastructure protection factor), evaluation scores were recomputed as shown in Table 6-16 and Figure 6-20.

Table 6-16: Assessment Results – Solution Preference When Infrastructure Protection is Discounted

	D/D/I	GNSS/INS	eLORAN
Weighted Score – Overall	0.679	0.692	0.665
Weighted Score – All AC	0.678	0.694	0.608
Weighted Score – All GA	0.673	0.684	0.708
Weighted Score – Gov/Stnds	0.68	0.702	0.679
Weighted Score – Total US	0.678	0.678	0.708
Weighted Score – US AC	0.668	0.671	0.643
Weighted Score – US GA	0.709	0.654	0.741
Weighted Score – US Gov/Stnds	0.668	0.715	0.712
Weighted Score – Total Europe	0.684	0.704	0.614
Weighted Score – Europe AC	0.688	0.717	0.578
Weighted Score – Europe GA	0.656	0.712	0.665
Weighted Score – Europe Gov/Stnds	0.695	0.688	0.631

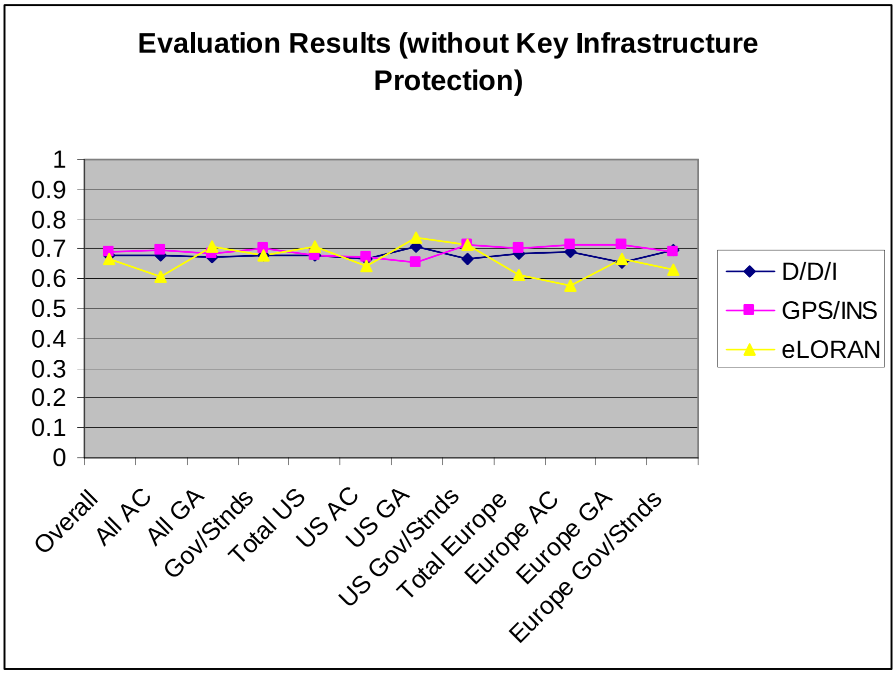

Figure 6-20: Assessment Results – Solution Preference (Infrastructure Protection Discounted)

In the results above, there is an adjustment in the candidate scores with the eLORAN becoming a slightly less preferable solution to GNSS/INS. For many stakeholders, GNSS/INS becomes the most preferable solution, but the preference over DME/DME/INS is marginal. Discounting the key infrastructure protection factor, the most preferable solution identified overall changes from eLORAN to GNSS/INS; however overall all candidates score closely and the preference of GNSS/INS over DME/DME/INS and eLORAN is marginal.

The results above indicate that there was some sensitivity in the results to the stakeholder set considered as well as to specific decision factors. Based on the stakeholder group considered and the set of evaluation factors considered, different SatNav backup solutions were identified as having the highest preference. Overall, there was a slight preference to the eLORAN solution for General Aviation. For commercial aviation, DME/DME/INS and GNSS/INS had a slightly higher preference to eLORAN. When cost was discounted, the preference leaned in the favor of DME/DME/INS; when key infrastructure protection was discounted, the preference leaned toward GNSS/INS. Based on the importance of decision factors assigned by government and standardization bodies, the eLORAN solution was the preferable candidate, but it was only marginally preferable over the other two solutions. When discounting cost, no impact to preference was identified, however when discounting the key infrastructure protection decision favor, preference shifted in favor of GNSS/INS for this stakeholder.

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7. RESULTS AND RECOMMENDATIONS

7.1 SATNAV BACKUP SOLUTION ASSESSMENT RESULTS & RECOMMENDATIONS

7.1.1 General Observations

A study methodology that considers a full set of operational concepts and requirements for navigation and utilizes direct stakeholder inputs has been applied in the assessment of candidate SatNav backup solutions. Interviews have solicited requirements and desires of stakeholders for both evaluation factors and alternative solutions to consider. Stakeholder interviews were also used to determine the relative importance of evaluation decision factors from their perspective. A set of identified backup alternatives were screened against threshold criteria that largely reflected technical requirements for a backup solution. Remaining candidate solutions were then assessed with regard to additional evaluation factors, with applied evaluation factor weights reflecting the importance assigned by stakeholders (determined through the stakeholder interview/survey process).

Applying the threshold criteria, three candidates were identified as applicable for providing a SatNav backup capability (where appropriate coverage of the system exists). These include the following:

- DME/DME/INS
- GNSS/INS, and
- eLORAN

One of the evaluating factors in the methodology was life cycle costs. A NPV cost model was developed to examine the relative costs of proposed SatNav backup solutions for applicable stakeholders. To estimate costs in a comparable fashion, several assumptions regarding the backup solutions were applied. These included a build-out of ground infrastructure (where applicable) for equivalent airspace coverage in the U.S. and an assumption that all aircraft accounted for in the stakeholder user groups would equip. SatNav backup solutions GNSS/INS and eLORAN were determined to have nearly equivalent NPV estimated costs of $4800 M. The estimated NPV cost for DME/DME/INS was $8200 M. These determinations guided the relative assessment of the solutions for the life cycle cost decision factor.

Overall, the final evaluation scores specific to these solutions indicate that there is not one SatNav backup solution that is significantly more preferable to all others for all stakeholders. eLORAN did have the highest preference rating overall and for the US aviation segments groups combined, performing more strongly for the General Aviation segment; but preference was only slightly above the other two candidates. Additionally, eLORAN does score third for some aviation segments, specifically some within the European categories.

The DME/DME/INS and GNSS/INS solution preference was only marginally different for many stakeholders, with preference of these solutions passing eLORAN when the Key Infrastructure Protection evaluation factor is discounted (GNSS/INS then has overall highest preference). Additionally, these solutions have higher preference over eLORAN for the air carrier segment.

When life cycle cost was discounted, there is a slight adjustment in the candidate scores with the DME/DME/INS becoming a slightly preferable solution over GNSS/INS. For many stakeholders, eLORAN is the most preferable solution, but the preference over DME/DME/INS is marginal. The differences in life cycle costs proved not a significant factor in the recommendations.

7.1.2 Time Phased Backup Solution Recommendations

To identify a backup concept strategy in the context of the NextGen operational concept, consideration needs to be given to the availability time frame for each of the candidate backup solutions. Each solution requires some development and deployment activities for implementation as follows:

- DME/DME/INS: Deployment of additional DME ground sites, installation of DME avionics and development/installation of INS avionics (development is for smaller/lighter implementations)
- GNSS/INS: Definition, development and deployment of ground reference capability to support synchronization of INS in terminal/surface environments in the advent of a localized GNSS outage
- eLORAN: Upgrade/buildout of ground infrastructure and standardization, develop and installation of eLORAN avionics

Based on the development and deployment activities required for each solution, a relative implementation risk for 2015 for each can be considered. For DME/DME/INS, this risk is low as much of the standardization and development work is completed or in progress; for GNSS/INS and eLORAN, this risk is moderate as both have standardization/development work required to implement a solution that is not started.

For 2020 and 2025, there may be sufficient time to reduce the implementation risk for all solutions such that all are viable candidates. In these time frames, the preference results noted above have more applicability.

Specific SatNav backup results/recommendations for the benchmark operational NextGen timeframes are provided in Table 7-1.

Table 7-1: SatNav Backup Results/Recommendations

	2015	2020	2025
Viable SatNav Backup Options	• DME/DME/INS	• DME/DME/INS • eLORAN • GNSS/INS	• DME/DME/INS • eLORAN • GNSS/INS
Recommendations for SatNav Backup	• DME/DME/INS	• DME/DME/INS • eLORAN • GNSS/INS	• eLORAN • GNSS/INS
Supporting Strategy	• Support DME/DME/INS as a backup solution (assume existing avionics and minimal build-out of DMEs • Continue support for eLORAN ground infrastructure upgrades • Continue support development of eLORAN avionics • Continue support development of smaller/lighter INS avionics	• Support transitioning a combined GNSS/INS and eLORAN solution (GNSS/INS as primary backup solution for Air Carrier complemented with eLORAN as primary backup solution for GA)	• Support GNSS/INS and eLORAN as SatNav backup solutions

The information in the table above indicates that in the 2025 timeframe, the recommendation is for support of eLORAN and GNSS/INS as capable and complementary SatNav backup solutions. eLORAN scored the highest overall preference rating in the analysis, particularly so in the U.S. and for the General Aviation stakeholder segment. eLORAN integration into GNSS/eLORAN FMS aviation systems for general aviation and certain air carrier segments could be a viable and capable solution.

This study also recognizes the uncertainties for expanding the eLORAN concept internationally and for achieving a global harmonization. The need for a backup solution outside of eLORAN coverage (including oceanic) necessitates an alternate and suitable backup for many air carriers. Based on the combined scores from all segments, and particularly for the Air Carrier segment, this study recommends GNSS/INS as the complementary backup solution. Note that although this candidate scores nearly identically to DME/DME/INS when considering all decision factors, its preference increased significantly when discounting the decision factor which addresses the desirability to protect key infrastructure.

It is expected that GNSS/INS systems would benefit from the additional blending of eLORAN positioning information where available. It could also assist with the early identification of drifting satellites. The GNSS/eLORAN/INS integration also addresses the concern for a SatNav backup that could sustain operations in a widespread outage beyond the coast distance of the INS.

Both GNSS and eLORAN meet a number of user PNT needs in addition to those in aviation. Once fully implemented the recurring O&M costs for eLORAN are reasonable compared with other ground NavAid options. To the benefit of users, the U.S. government provides GPS services. Low infrastructure costs mean that there is little cost penalty for adopting this dual back-up recommendation for 2025.

With low infrastructure costs attributable to aviation, the costs for either eLORAN or GNSS/INS SatNav backup solution will scale with the number of users that equip. The type of flight operations conducted and equipage costs will determine the user preference of the two alternatives.

7.2 AREAS FOR FUTURE STUDY

In this study, several promising technologies aviation navigation technology areas were explored. These included:

- GNSS/INS where the INS component is a very low cost inertial elements in a very tight coupling with GNSS. The INS would likely not have suitable drift rates that could provide any significant coasting but would be compact, light weight, and inexpensive. The benefit then is not in significant coasting ability but rather in improved signal to noise ratio that could be achieved with a corresponding improvement in tolerance to interference. This was one element of the ‘hardened GNSS’ concept. Potentially, this technology could provide very affordable aids for general aviation.
- The Terrain Reference Navigation concept for civil aviation has a strong appeal in that it is autonomous, and could potentially sustain aviation operations in all phases of flight operation, except oceanic.
- The research and development of a ground based Low Frequency (LF) PNT system with improved accuracy, integrity, and data handling capacity (cf. eLORAN). The objective is a ground based PNT system that could provide capability to support aviation performance requirements < RNP-0.3. This would add important additional adaptability as a SatNav backup. Such a system could possibly better meet the conjoint requirements as backup for both aviation navigation and surveillance.
- The concept for a ground reference position fix for an inertial system was created in this study to enable GNSS/INS equipped aircraft to take off and perform required RNP operations to exit a terminal area. This ground reference and additional surface operation requiring accurate positioning appear to be synergistic with similar requirements being studied for the Intelligent Transportation System by the Federal Highway Administration (FHWA).
- Precision approach navigation aids other than the existing ILS and MLS systems were not identified in the study as capable SatNav backups for meeting the requirements of CAT I/ II/ and III operations. With the desire to remove ILS/MLS systems, and in the demanding future environment of more tightly spaced runways, an alternate candidate should be developed or identified.

APPENDIX A. BIBLIOGRAPHY

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- *U.S. Space Based Positioning, Navigation and Timing Policy*; Dec. 15, 2004.
- *The Federal Navigation Plan,* Version cited for this study: 2005, Homeland Security, DOT, noted also below.
- *Homeland Security Presidential Directive/HSPD, Subject: Critical Infrastructure Identification, Prioritization and Protection*; December 17, 2003.

Received Materials at Preliminary Meeting 11/6/06:

- Presentation material from Doug Arbuckle (11/6/06): NSSO: '*National PNT Architecture Decision Coordination Group #1'*, 31 Aug 06
- From Karen VanDyke (11/6/06) '*National Positioning, Navigation and Timing Architecture, Terms of Reference'*

Key FAA Transition Strategy Documents

- White Paper: *GPS Backup for Position, Navigation, and Timing; Transition Strategy for Navigation and Surveillance*, Lilley, Church, and Harrison (Aviation Management Associates, Inc), for FAA, Aug 22, 2006.
- *Navigation and Landing Transition Strategy*, FAA, 2002.
- *Roadmap for Performance-Based Navigation, Evolution for Area Navigation (RNAV) and Required Navigation Performance Based (RNP) Capabilities, 2006-2025,* Version 2.0, FAA, July 2006.

NGATS/JPDO Reference Documents

- *Next Generation Air transport System Integrated Plan*, http://www.jpdo.aero/integrated_plan.html.
- *2005 Progress report to the Next Generation Air transport System Integrated Plan*. http://www.jpdo.aero/integrated_plan.html
- *Concept of Operations for the Next Generation Air Transportation System*, Version 2.0, June 13, 2007.
- *NGATS 2025 Concept*, v4.8 Public, Aug. 31, 2005, http://techhangar.jpdo.aero/

RTCA Reference Documents

- *RTCA DO-202 Report of Special Committee 159 on Minimum Aviation System Performance Standards (MASPS) for Global Positioning System,* Nov. 1988
- *RTCA DO-208 Minimum Operational Performance Standards for Airborne Supplemental Navigation Equipment Using Global Positioning System (GPS),* July 1991

- *RTCA DO-229C Minimum Operational Performance Standards for Global Positioning System/Wide Area Augmentation System Airborne Equipment*, November 2001.
- *RTCA DO-236B Minimum Aviation System Performance Standards: Required Navigational Performance for Area Navigation*, October 2003.
- *RTCA DO-247 The Role of the Global Navigation Satellite System (GNSS) in Supporting Airport Surface Operations,* Final Draft, November 1998.
- *RTCA DO-283A Minimum Aviation System Performance Standards for Required Navigational Performance for Area Navigation*, October 2003.
- *RTCA Task Force 1 Report on Global Navigation Satellite System (GNSS) Transition and Implementation Strategy*, Sept. 1992.
- RTCA National Airspace System Concept of Operations, Dec. 2000.
- RTCA National Airspace System Concept of Operations Addendum 4: Free Flight Phase 2, 2000.
- RTCA National Airspace System Concept of Operations and Vision for Future Aviation, 2002.

ICAO International Civil Aviation Organization

- *European Regional Area Navigation (RNAV) Guidance Material*, 5th edition, Sept, 2003.
- *Performance Based Navigation Manual*, Working Draft 5.1–Final, March, 2007.

LORAN Specific Reference Documents

- '*LORAN for RNP 0.3 Approach: The Preliminary Conclusions of LORAN Integrity Performance Panel (LORIPP)*; Sherman Lo, Per Enge, Ben Peterson, Bob Wenzel, Peter Morris, Lt. Kevin Carroll.
- *LORAN Integrity Analysis for Required Navigation Performance 0.3*; Sherman Lo with co authors Ben Peterson, Per Enge, Robert Wenzel, G.Gunther, Peter Morris, Lt. Kevin Carroll.
- *LORAN's Capability to Mitigate the Impact of a GPS Outage on GPS Position, Navigation, and Time Applications for FAA*, March 2004.
- *Common-View LORAN-C as a Backup to GPS for Precise Time Recovery*, Celano, Carroll, Biggs, and Lombardi.
- *The Case for eLORAN, Research and Navigation*, General Lighthouse Authorities of the United Kingdom and Ireland; May 8, 2006.
- *The Potential Role of Enhanced LORAN-C in the National Time and Frequency Infrastructure*, Lomardi, Celano, Powers.
- *Independent Assessment Team (IAT) Summary of Initial Findings on eLORAN*, Presentation to DOT and DHS POS-NAV Executive Committees, 20 March 2007, v4.

Other Briefing Materials

- *NGATS Analysis-Inertial Backup*, simulation study by Honeywell performed and submitted by Honeywell at the request of this study, June, 2007.

- *Integration of GNSS and Inertial Navigation Systems*, International Coordination Council of Aerospace Industries Associations (ICCAIA), presentation paper to the Eleventh Air Navigation Conference, Montreal, 2003.
- *GPS Status and Modernization*, Briefing to the National PNT Advisory Board, 29 March 2007, Col. Allan Ballenger.

System Engineering and Cost Reference

- *National Airspace System*, *System Engineering Manual***,** FAA ASD-100 Architecture and System Concepts of Use for New Technology Candidates
- *NASA Cost Estimating Handbook*, National Aeronautics and Space Administration, 2004.
- *FAA Life Cycle Cost Estimating Handbook*, version 0.2, Federal Aviation Administration Investment Cost Analysis Branch, ASD-410, June 3, 2002.
- *Modular, Cost-Effective, Extensible Avionics Architecture for Secure, Mobile Communications*, William D. Ivancic, NASA/GRC

SESAR and EUROCONTROL

- *Navigation Strategy for ECAC*, edition 2.1, European Air Traffic Control Harmonisation and Integration Programme, EUROCONTROL

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APPENDIX B. SATNAV BACKUP OF AIRPORT SURFACE OPERATIONS

B.1 AIRPORT SURFACE OPERATIONS

Satellite navigation when augmented to meet the requirements for precision landings is also expected to enable surface navigation to 1.5 – 2.0 meter accuracy. This capability will enable equivalent visual operations[83] [84] in all weather conditions and surveillance strategies for achieving situational awareness with other aircraft as well as ground vehicles.

B.2 SURFACE OPERATION POSITIONING REQUIREMENTS

RTCA DO-247, The Role of the Global Navigation Satellite System (GNSS) in Supporting Airport Surface Operation presents material on airport surface operations. This document notes that the "see and be seen" principle is the common current support for guidance and surveillance functions. Advanced systems may have switched taxiway or centerline lighting, stop bars, and surface movement radar data that may augment visual observations.

RTCA DO-247 identifies GNSS as an enabler to airport surveillance and surface navigation systems. GNSS enabled ADS-B is expected to be an essential component in system architectures to provide the improved situation awareness and the display of other aircraft and vehicles.

RTCA DO-247 includes classifications of airport environments and for airplane design. The movement area travel surface width for the airplane design groups and for airport codes are summarized for runway and taxiway operations. The containment limit concept is used to define requirements for deviation from a centerline course. For runways and taxiways, the most demanding lateral position requirement is for the wheel offset to the edge of the travel surface. Normal requirements (95% TSE satisfied) are derived and are on the order of ±2.2 meters for rapid exit, normal, and apron taxiways; ± 1.2 meters for taxi lanes, and ± 1 meter for parking and docking operations.

[83] JPDO CONOPS for the Next Generation Air Transportation System explains Equivalent Visual Operations: "Improved information availability allows aircraft to conduct operations without regard for visibility or direct visual observation. For aircraft, this capability, in combination with PNT, enables increased accessibility, both on the airport surface and during arrival and departure operations. This capability also enables those providing services at airports (such as ATM or other ramp services) to provide services in all visibility conditions, leading to more predictable and efficient operations."

[84] A technology called Enhanced Vision System (EVS) detects and measures infrared radiation intensity within a field of view from one or more wavelengths. A processed infrared image of the field of view is developed and presented to the pilot as an aid intended to improve visual awareness in darkness or some poor weather conditions. The effectiveness of EVS is dependent on the intensity and variation of radiation energies from the objects in view (a function of material emissivities, temperatures, distances, and absorption characteristics of the atmosphere at the wavelengths used). EVS does not provide position coordinates useful for a navigation or surveillance systems. It is noted since it has potential to enhance crew 'visual' awareness for visual operations.

These surface positioning and navigation tracking requirements will require augmentations of the GNSS. These positioning requirements are a particular challenge for a SatNav backup candidate to satisfy.

Surveillance requirements are generally less demanding with accuracy requirements (95%) on the order of 10 meters. Augmented GNSS will enable ADS-B to satisfy these requirements. The surface surveillance requirements are also a challenge for systems to satisfy in the absence of GNSS.

B.3 SATNAV BACKUP CANDIDATES FOR SURFACE OPERATIONS

Study team candidates for SatNav backup for surface operations are listed in Table B-1.

Table B-1: SatNav Backup Candidates for Surface Operations

SatNav Backup Candidate for Surface Operations
Primary ground radar
Concept of Multilateration with A/G data link
Inertial guidance with position and orientation from a ground reference position
eLORAN with differential augmentation
Hardened GNSS system
Follow me carts
Special sensors: embedded surface markers, 'you are here' beacons, RFID, etc

B.4 ASSESSMENT OF SATNAV BACKUP CANDIDATES FOR SURFACE OPERATIONS

This study performed only a high level assessment of the candidates against the navigation and surveillance requirements noted.

B.4.1 Primary Ground Radar

Radar for surface applications has technical limitations including coverage and multipath. Multiple airport systems would be required for coverage without gaps or blind spots. Radar systems are also susceptible to multipath that can result in identification of false target positions. Ground radar with verbal guidance from a ground controller can help with general guidance (which taxiway, notice of other moving aircraft or vehicles). This candidate cannot meet the needs for navigation guidance to maintain centerline tracking on runways or taxiways.

B.4.2 Multilateration

RTCA DO-247 Section D.6.2 presents airport surface multilateration test results that generally had position accuracy better than 10 meters. The test utilized ground receiver/transmitter stations that performed the multilateration function on Mode-S transmissions. From a coordinated measurement of time of arrival at a minimum of three stations, position was computed.

B.4.3 Inertial Guidance

An extension of the simulation study presented in Section 4.1.2.3.5 was conducted by Honeywell to help answer the questions about the application of aircraft INS systems to provide surface position navigation guidance in the absence of GNSS.

B.4.4 eLORAN

eLORAN, with location specific correction factors, could be expected to support position accuracies on the order of 20 meters. Reference Section 4.1.2.2 for additional discussion of eLORAN.

B.4.5 Hardened GNSS system

The attributes of this candidate are discussed in Section 4.1.2.5. This candidate would satisfy both the airport surface navigation and surveillance requirements that could be derived from GNSS and supported with ADS-B. This candidate is not a true backup in the sense that it is not independent of GNSS. It could be expected to reduce the affected area of an interference event. This candidate is expected to be costly, difficult to retrofit into aircraft, and controlled by export regulations.

B.4.6 Follow-me Cart

This candidate is not elegant but nicely practical. In poor visibility conditions, the ground carts would lead with visual guidance or with additional communications for navigation support to the aircraft. This candidate helps with surface navigation but does not assist surveillance, other than with radio voice communication of position relative to centerlines, exits, docking points, etc.

B.4.7 Special Sensors

The development and application of new sensor and positioning technology could potentially meet the combined requirements for airport surface navigation and surveillance. Some synergy between the needs for airport surface navigation and those for the Intelligent Transportation System[85](ITS) initiative appears to exist.

The positioning requirements for the ITS at a high level are an accuracy (95%) of less than 5 meters to determine ‘which road’, less than 1 meter to determine ‘which lane’, and < 0.3 meters to determine ‘where in the lane’. Other requirements of a positioning system such as availability, integrity, continuity, etc. are expected to be determined close to the time this study report is completed.

GNSS with augmentation is expected to be an important enabler for certain of the ITS needs while additional solutions may be required for more localized and critical needs. The field of possible candidate local positioning solutions for the ITS include pseudolites, in-pavement sensors, and infrastructure based radar.

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[85] *ITS Vehicle-Information Integration (VII)*, brief to the PNT Architecture Development Team April 18, 2007.

Assuming 1.5-2.0 meter accuracy of the primary GNSS navigation with augmentation, several of the requirements for airport surface operations would not be achievable. With these assumptions, some blending of GNSS and specialized position sensors would be necessary for primary navigation guidance.

B.5 ASSESSMENT SUMMARY OF SATNAV BACKUPS FOR AIRPORT OPERATIONS

Table B-2: Assessment of SatNav Backup Candidates for Surface Navigation

Surface operation	**SatNav Backup Candidate for Surface Navigation**						
	Navigation Accuracy (95%) Requirement	Primary Ground Radar	Multi-lateration	INS	eLORAN	Hardened GNSS system[86]	Special sensors
Identify exit taxiway	± 20 m (estimate)	Yes	Yes	Yes[87]	Marginal	Yes	Likely
Taxiway track	± 2.2 m	No	No	No	No	Yes	Likely
Taxilane track	± 1.2 m	No	No	No	No	No	Likely
Docking	± 1.0 m	No	No	No	No	No	Likely

For surveillance requirements of 10 meter (95%) accuracy or less, the following could be applied:

- Multilateration
- INS
- Special sensors

B.6 SIMULATION STUDY TO EVALUATE INS PERFORMANCE FOR SURFACE OPERATIONS

The Honeywell simulation study presented in Section 4.1.2.3.5 was extended to include an analysis of the capability of an inertial system for airport surface navigation. An assumption is the added architecture element, a method to receive position updates while on the surface. The exact method is not important to the study but could require embedded surface sensors, ‘you are here’ beacons, or crew initiation.
The study looked at several scenarios:

- Case 1: Update from GNSS then loss while on the surface,
- Case 2: A surface position (not GNSS) update is obtained on touchdown, and
- Case 3: Surface position (not GNSS) update while stationary with no prior history of GNSS calibration.

[86] The hardened GNSS candidate is not a true backup in that it is dependent on GNSS. Its assessment would logically be that of the primary, GNSS and necessary augmentations.
[87] Assumed accurate (95%) 1 meter ground point position fix at touchdown point or other strategic ground positions and the subsequent coast time for (R95) 10 meter accuracy of 2.5 minutes.

As expected, the best case performance is Case 1 that follows a GNSS calibration and the ground position update. The most limited case would be Case 2 for a landing aircraft with moving ground position update (no prior GNSS calibration). These coasting times are much smaller compared to Case 1 for two reasons:

1. The inertial system is not calibrated
2. The velocity errors are not corrected by the position update at the time of landing.

Case 3, with the inertial calibrated only from a ground reference, without GNSS, and with the system stationary, had slightly longer coast times than Case 2. This is because with the aircraft stationary, there is no velocity error built up in the system.

R95 Coasting Performance – Taxiing (Case 1) Honeywell

R95 (meters)	Coasting time (minutes) for GPS/INS^	Coasting time (minutes) for GPS/HAINS with Gravity Compensation^
2.0	2.25	3.0
5.0	4.25	5.5
10.0	6.25	8.0

^ This analysis assumes a position update from some source of precise "runway" position fix (1 meter – R95) at the time of landing prior to coasting and GPS aiding of the inertial prior to the position update

Figure B-1: Summary of Predicted Taxiing Coasting Performance for Case 1

R95 Coasting Performance – Taxiing (Case 2) Honeywell

R95 (meters)	Coasting time (minutes) for GPS/INS^	Coasting time (minutes) for GPS/HAINS with Gravity Compensation^
2.0	0.5	1.0
5.0	1.25	2.5
10.0	2.5	4.25

^ This analysis assumes a position update from some source of precise "runway" position fix (1 meter – R95) at the time of landing prior to coasting and "no" GPS aiding of the inertial prior to the position update

Figure B-2: Summary of Predicted Taxiing Coasting Performance for Case 2

R95 Coasting Performance – Taxiing before Takeoff

R95 (meters)	Coasting time (minutes) for GPS/INS^	Coasting time (minutes) for GPS/HAINS with Gravity Compensation^
2.0	2.0	2.25
5.0	3.25	3.75
10.0	4.25	5.0

^ This analysis assumes an accurate position update while the aircraft is at the terminal before taxiing for takeoff

^ Since the aircraft is not moving during the position update there is no calibration of the inertial system and so the coasting times are smaller compared to the approach case 1 with GPS aiding

^ Starting velocity errors are zero since the aircraft is not moving and so the coasting times are larger compared to the approach case 2 without GPS aiding

Figure B-3: Summary of Predicted Taxiing Coasting Performance for Case 3

APPENDIX C. SATNAV BACKUP FOR PRECISION APPROACH

Today, the requirements for precision approaches defined by Category (CAT) I, II, and III are enabled by ground based radio navigation aids. In the U.S., the principal ground aid is the Instrument Landing System (ILS). An ILS is composed of a localizer to provide horizontal guidance, a glide slope indicator to provide vertical guidance, runway markings, and approach and runway lighting. The Microwave Landing System (MLS) also fills the role of an all weather precision landing system. MLS have no significant role in the U.S., with just a few remaining in service for research and testing. Europe has implemented MLS at a number of airports but ILS is the predominant system.

The JPDO NextGen CONOPS discusses more flexible airport planning following the decommissioning and removal of ILS systems, enabled by the expected primary SatNav capability. The motivation for an alternative backup solution other than ILS are the cost to operate and maintain these systems, the sensitivity of the antennae array patterns to local structures and movement, and the difficulty in supporting narrowly separated parallel runways. Eliminating ILS systems would provide flexibility in the layout design of new or expanding airports.

Satellite navigation[88] enables aircraft to perform LPV procedures where they are approved. By 2025, satellite based navigation with augmentation may be an enabler for aircraft to perform equivalent CAT I, II, and III precision approach and landing operations. The principal challenges in meeting these goals are the vertical accuracy requirements and the integrity issues where a minimal delay to alert for hazardously misleading information from the navigation system is required.

C.1 POTENTIAL CANDIDATES FOR PRECISION APPROACHES

None of the candidates from the mandated candidates for area navigation (DME/DME/INS, eLORAN, or GNSS/INS) provide the necessary capability for precision approach. The stakeholders proposed the present navigation aids:

- ILS (from U.S. stakeholders)
- ILS or MLS (from European stakeholders)

The project team added the following candidates:

- Hybrid ILS (retention of glide slope indicator, some other system provides horizontal guidance)
- eLORAN or Multilateration for horizontal guidance, altimeter providing vertical guidance
- Hardened GNSS system

[88] GPS + Wide Area Augmentation System (WAAS)

- Terrain Reference System

Precision approaches are a formidable operational challenge for a SatNav backup system, apart from the traditional reliance on ILS and MLS. Some of these candidates were not considered adequate for CAT I precision landing support but could potentially reduce decision heights from current non precision approach requirements.

Table C-1: SatNav Backup Candidates for Precision Approach

Precision Approach SatNav Backup Candidate
ILS or MLS (current NavAid for precision landings)
Hybrid ILS (eLORAN or multilateration, with retention of glide slope indicator)
eLORAN or multilateration, with altimeter providing vertical guidance
Hardened GNSS system
Terrain reference navigation system

C.2 DESCRIPTION OF CANDIDATES FOR PRECISION APPROACHES

C.2.1 ILS, Glide Slope Indicator and Localizer

A precision approach must be made on a path aligned with the runway and with a controlled and precise descent. In poor weather or conditions with poor visibility, precision approaches are accomplished with ILS[89] navigation aids: localizer, glide slope indicator, and possibly marker beacons. Along with the radionavigation aids, other ILS components that enable operations in poor weather include runway markings and approach and runway lighting.

The localizer antenna is positioned at the end of the runway and radiates a signal that is aligned with the runway centerline and is modulated with two tones. The ILS navigation receiver determines if the aircraft is left, right, or on centerline and provides lateral guidance. The glide slop also radiates a signal modulated with two tone pattern. ILS navigation receiver determines if the aircraft is vertically above, below, or on the correct decent path. An ILS is said to provide both horizontal and vertical guidance.

ILS provides very precise guidance in this precision approach phase of flight operations. SatNav with local augmentation is expected to provide the necessary 3-D positioning accuracy and the necessary integrity for aircraft navigation to perform precision approach and landings. It will be a significant technical accomplishment when SatNav reaches this performance level. It is also a challenge for any navigation system to satisfy the requirements of this application now performed by ILS.

The retention of ILS is a candidate for the role of SatNav backup for precision approaches, at least for major airports.

[89] Microwave Landing Systems (MLS) have certain advantages over ILS but are few in number compared with the ILS.

C.2.2 Hybrid: Glide Slope + eLORAN or Multilateration

This candidate was conceived assuming there would be benefit to removing the localizer component of the ILS and retaining the Glide Slope. Candidates to provide horizontal guidance were eLORAN and Multilateration. eLORAN would require local correction factors, possibly differential, to achieve predictable horizontal accuracy to 20 meters. With appropriate sighting, Multilateration accuracy on the order of 10 meters could be expected.

Either option would have many technical hurdles and at best, the hybrid could not meet the performance requirements for a CAT I approach. Lateral position navigation accuracy and integrity are key concerns for this precise operation. eLORAN would merit further consideration if it was also determined to be the SatNav backup for area navigation. Multilateration, unless provided in some other context such as surveillance, would be complex and expensive to add.

Optimistically, this hybrid concept might satisfy requirements for some approach classification with a lower decision height than a non precision approach.

C.2.3 eLORAN or Multilateration + Altimeter

Expected performance capability of eLORAN and multilateration components were noted in the preceding subsection. The altimeter component would result in higher decision heights than for retention of the glide slope indicator. This concept if developed would be applicable to smaller airports and general aviation.

C.2.4 Hardened GNSS

The description of a hardened GNSS navigation system is given in Section 4.1.2.5. The candidate is not a true GNSS backup but could help mitigate the issue of interference. Cost and policy are obstacles for employing these technologies to civil aviation.

C.2.5 Terrain Reference Navigation (TRN) System

Description and capabilities for both laser and radar based terrain navigation systems are provided in Section 4.1.2.6. The addition of the terrain tracking assists the inertial system in helping to bound error growth during periods of coasting. The terrain tracking component also provides the geometric height of the aircraft, useful for approach. TRN systems have demonstrated the ability to provide navigation with real time computation over the final precision approach phase[90]. The requirements for integrity, availability, coverage, and continuity to support precision approach are important and possibly difficult performance metrics for TRN systems to achieve for this critical phase of flight operations.

[90] *Application of Airborne Laser Scanner – Aerial Navigation*, 2006, PhD Dissertation, Russ College of Engineering and Technology of Ohio University, Jacob L. Campbell

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APPENDIX D. ROUND 1 STAKEHOLDER INTERVIEW LETTER & QUESTIONNAIRE

Wayne Genter, PhD
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Advanced Engineering & Sciences

ITT Corporation

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email wayne.genter@itt.com

February 9, 2007

To: STAKEHOLDERS

Subject: Request for participation in the NGATS Institute Satellite Navigation Backup Study

Dear Colleagues,

The purpose of this letter is to invite the participation of aviation community stakeholders in a satellite navigation backup study. This study for the Next Generation Air Transportation System (NGATS) Institute, in cooperation with the Joint Planning and Development Office (JPDO), is aimed at identifying appropriate backup solutions for satellite navigation to:

- meet the minimum set of navigational and secondary use requirements;
- be cost effective;
- be reliable;
- and ideally available world-wide.

The study is viewed as a trade study and will reflect the voices of the aviation community stakeholders.

Your organization has been selected as a representative for your segment of the industry, so your voice will be valued and bear significant weight in the recommendations of this study.

The navigational capability of an aircraft is derived from its ability to accurately determine position in 3D space and time. Currently this is achieved by a combination of technologies from terrestrial and celestial sources. The celestial source is provided by satellite navigation and may be subject to interference atmospheric anomalies, or system failure, which could, in a future scenario, render the capability of the aircraft to determine its position for navigational purposes, or for position reporting (such as in ADS-B[91]), below acceptable standards for the management of air traffic. For the future concept of operations of NGATS, the use of accurate 4D trajectories, RNP, RNAV and co-operative surveillance will require the ability to accurately determine an aircraft’s position.

The study is first considering the user requirements for a system (if deemed necessary) to provide an alternate source of navigational information to allow the accurate determination of an aircraft’s position. This use of a back-up source of technology will be necessary should the current satellite navigation information be rendered unavailable. It is important in high density airspace, or in critical phases of flight, that navigational accuracy, integrity, and continuity be maintained in order to keep the national airspace operating safely and at capacity.

[91] Automatic Dependent Surveillance Broadcast

We are planning two rounds of interviews, each designed to solicit the necessary stakeholder inputs, while appreciating the value of your time. The first interview is designed to be completed within 20 minutes and will develop the stakeholder requirements, including performance and cost, of a satellite navigation backup system. Following team analysis of the responses, the study team will identify decision factors. A second interview will solicit comparative weightings for these decision factors. Following the application of the Analytic Hierarchy Process, the voice-of-the-customer techniques will identify the recommended backup solutions from the aviation stakeholders.

All information received will be treated in the utmost confidence and will be un-attributable to either yourself or your organization. We value your honest opinion and as such, we provide assurance that your responses will not be divulged to anyone outside the project team.

Your willingness to participate in this study will be confirmed by one of the project team. Thank you for you consideration for providing your voice in this study.

Sincerely,

Satellite Navigation Backup Study team
Wayne Genter, PhD – ITT AES
Andy Taylor – QinetiQ
Dr. Trent Skidmore – Ohio University Avionics Engineering Center

Wayne Genter PhD, PE
Senior Principal Engineer
Advanced Engineering & Sciences

Satellite Navigation Backup Study for NGATS Institute
Stakeholder Round 1 Interview Form rev 2/26/2007

Stakeholder Interviewee Information

Name: ______________________________
Position: ______________________________
Organization / Department: ______________________________
Responsibility concerning Air Navigation: ______________________________
____
____
Telephone: ____________________ email ____________________
Postal Address: ______________________________
____
____
Interviewer(s) ______________________________ Interview Date ___ /___ / 2007
______________________________ mm dd

Do you have any questions before we proceed?
Fine, the first question looks not just at today, but projects into the future.

(1) What do you see as your usage of satellite-based navigation today and your reliance upon it in the 2025 timeframe?
Today …

Future …

The next two questions assume the larger role of satellite navigation into the future (say 2025). These questions consider operations and cost.

(2) What do you consider the *operational* implications to your organization if Satellite based navigation was rendered unavailable for time intervals as short as 3 minutes or as long as 3 days?

3 minutes …

3 days …

The previous question looked at the operational implications, the following similar questions concerns cost.

(3) What do you consider the *cost* implications to your organization if Satellite navigation was rendered unavailable for time intervals as short as 3 minutes or as long as 3 days?

3 minutes …

3 days …

The fourth question is rather pointed.

(4) Do you think a backup to Satellite based navigation is necessary (for your organization)?

☐{If Yes – What are the necessary (cost, performance) requirements of a backup system in terms of performance and cost?}

☐{If No – Can you expand on your answer?} ☐{If Don't Care – Why don't you care?}

The final question has two parts and gives you the opportunity to be a long-term strategic planner.

(5)What would be your recommendations for satellite navigation backup in view of the paradigm of RNP, RNAV, and 4-D trajectories as the NAS airspace evolves through 2025?

And the 2nd part of the question …

What factors were important in preferring this satellite navigation backup solution over other candidates?

Now, I am going to sum up the main ideas and opinions you expressed during this interview. I would like to confirm that I have understood your point. Feel free to tell me if not or to illustrate a point when you feel it is necessary.

Summarize from your notes. Provide pauses and allow time for confirmation or possible modifications.

At the end of the interview,

- *As I assured earlier, your opinions will be treated confidentially and will not be attributable to either you or your organization. Your information will be compiled with that from other aviation stakeholders and used by the project team in this study. Your inputs will help guide the recommendations that will be published at the conclusion of this study.*
- *Well. Thank you very much indeed for your participation and all your useful comments.*

Note here any additional comments outside the answers to our prepared questions.

APPENDIX E. ROUND 2 STAKEHOLDER INTERVIEW QUESTIONNAIRE

Wayne Genter PhD, PE
Senior Principal Engineer
Advanced Engineering & Sciences

Satellite Navigation Backup Study for NGATS Institute
Stakeholder Round 2 Interview Form rev 5/17/2007

Stakeholder Interviewee Information

Name: ______________________________
Position: ______________________________
Organization / Department: ______________________________
Responsibility concerning Air Navigation: ______________________________
____
____
Telephone: ______________ email ______________
Postal Address: ______________________________
____
____
Interviewer(s) ______________________ Interview Date ___ /___ / 2007
______________________ mm dd

The purpose of this interview is to understand stakeholder views and values concerning factors important in selecting systems as a backup to satellite-based navigation. *(This is an important issue as satellite navigation is an important enabler in NEXGEN and SESAR visions for future operations.)* In these questions, we assume that satellite navigation is the primary navigation aid.

I will be asking a number of questions. Each question will compare two factors. You will be asked to select if the two factors are equally important, or if one is more important that the other.

Example of how we will compare two factors.
As an example, if we were determining the importance of factors in selecting a new automobile, we might want to compare the factors performance to economy.

I would then ask for your comparison of the factors: **economy** and **performance.**
You could indicate that they were equally important or that one was more important than the others.

If one was more *(or less)* important than the other, a question will be asked to determine the degree of your preference.
You could indicate that one factor is:

- Moderately
- Strongly, or
- Very strongly

more important than the other.

Car with good **economy**	☐ equally important ☐ moderately ☐ strongly ☐ very Strongly	☐ < equal > ☐ more important ☐ less important	Car with good **performance**

For each series of questions, I will first review the factors that we will compare. For the automobile selection example, I might have indicated at the beginning that we will compare the factors:

- Economy,
- Performance, and
- Prestige.

and then proceed with pair-wise comparisons.

Also, I will review the meaning of the factors and answer any questions. If anything is not clear, I will help.

Do you have any questions at this point?

Are we ready to proceed?

Redundant Capability and minimal Operation impact
With different SatNav Backup systems, there are a range of capabilities

This factor addresses the capability of the backup compared with satellite based navigation. It considers whether the backup allows the user to meet the **same navigation performance**, whether the backup is **continuous** or **degrades with time**, and whether the need for backup requires **immediate crew and ATC response**.

In a sub-survey, a comparative question is presented to better understand user opinions by comparing three scenarios:

- **Seamless failover, redundant performance**
  Virtually seamless failover (no immediate crew or ATC procedures invoked) from GNSS when required. Capable for the long term sustaining of operations and could be co-prime with GNSS for all US performance based (en route, terminal, and Non Precision Approaches) navigation requirements.

- **Seamless failover, redundant for only 30 minutes as capability degrades**
  Virtually seamless failover (no immediate crew or ATC procedures invoked), but could sustain present level of navigation performance only for 30 minutes as accuracy degrades.

- **Immediate reduction in navigation capability, may require crew and ATC actions** The SatNav backup could provide reduced navigational performance capability. When required, different procedures may be required. Training for this possible loss of primary SatNav would be required to ensure safety. Ground navigation control would immediately invoke procedures such as increasing separation minima to account for reduction in performance capability.

Global harmonization (not including Oceanic)

The next set of questions compares the relative importance of the backup solution being available on a regional basis or globally.

This would be important to international carriers wanting to minimize equipage. We are considering navigation over land, not oceanic.

In the next questions, I will ask you to compare three degrees of harmonization:

- The SatNav backup is supported almost **globally**.
- The SatNav backup is supported in most important global markets, **North America, Europe, and North Pacific Asia**. Further coverage can be made available with modest infrastructure cost.
- North America and Europe identify **separate strategies** to provide a backup to satellite based navigation in their regions.

Life Cycle Cost

This factor measures the importance of life cycle cost to equip and maintain a backup solution.

Here, we will just compare two views:

- The SatNav backup has the lowest total life cycle cost for the combined infrastructure and all aviation users.
- The SatNav backup has the lowest user costs in my aviation segment but could have a higher total aviation industry wide (infrastructure + all users) cost to sustain it compared to other options.

Early Avionics Availability

Some backup system solutions for the 2025 and beyond period may not have available equipage in the immediate future. An example would be a new technology.

Other backup solutions using traditional navigation aids would support the needs of users until the proposed backup avionics are available.

This factor measures the tolerance or concern of not being able to equip new aircraft or re-equip existing aircraft with the backup solution. .Here, we are looking to assess whether it is important that avionics supporting the backup would not be available by:

- 2010.
- 2015.
- 2020.

(If this is a don't care, mark the choices all equal.)

Round 2 Stakeholder questionnaire

Sub-survey: Redundant Capability and minimal Operational Impact
This first set comparisons present operational issues when GNSS is unavailable and the Satellite Backup system is required. We are now considering en route, terminal, and non precision approach phases of flight, **not** oceanic or precision approaches.
The phrase '**seamless transition**' has the meaning that when the backup is required, no immediate crew or air traffic control procedures are required.

Seamless transition, redundant performance	☐ equally important ☐ moderately ☐ strongly ☐ very Strongly	☐ < equal > ☐ more important ☐ less important	Seamless transition, redundant for only 30 minutes as capability degrades
Seamless transition, redundant performance	☐ equally important ☐ moderately ☐ strongly ☐ very Strongly	☐ < equal > ☐ more important ☐ less important	Immediate reduction in navigation capability, may require crew and ATC actions
Seamless transition, redundant for only 30 minutes as capability degrades	☐ equally important ☐ moderately ☐ strongly ☐ very Strongly	☐ < equal > ☐ more important ☐ less important	Immediate reduction in navigation capability, may require crew and ATC actions

Sub-survey: Global harmonization (not including Oceanic)
The next set of questions compares the relative importance of the backup solution being available globally.

A common SatNav backup strategy is **supported globally**. The backup is supported all regions.	☐ equally important ☐ moderately ☐ strongly ☐ very Strongly	☐ < equal > ☐ more important ☐ less important	The common SatNav backup is supported **in most important global markets**, North America, Europe, and North Pacific Asia. Further coverage can be made available with modest infrastructure cost.
A common SatNav backup strategy is **supported globally**. The backup is supported all regions.	☐ equally important ☐ moderately ☐ strongly ☐ very Strongly	☐ < equal > ☐ more important ☐ less important	**North America** and **Europe** identify separate strategies to provide a backup to satellite based navigation in their regions.
The common SatNav backup is supported **in most important global markets,** North America, Europe, and North Pacific Asia. Further coverage can be made available with modest infrastructure cost.	☐ equally important ☐ moderately ☐ strongly ☐ very Strongly	☐ < equal > ☐ more important ☐ less important	**North America** and **Europe** identify separate strategies to provide a backup to satellite based navigation in their regions.

Sub-survey: Life Cycle Costs
The next question compares the relative importance of life cycle cost concerns. The term 'user costs' are the life cycle costs that would be incurred to aid and maintain SatNav backup avionics (either retrofit or new aircraft build), and any required certification and training.

The SatNav backup has the lowest total life cycle cost for the **combined infrastructure and all aviation users**. .	☐ equally important ☐ moderately ☐ strongly ☐ very Strongly	☐ < equal > ☐ more important ☐ less important	The SatNav backup has the lowest user costs in **my aviation segment** but could have a higher total aviation (infrastructure + all users) cost to build and sustain it.

Sub-survey: Early Commercial, Certified Avionics Availability

The next set compares the time when SatNav backup avionics are first available.   New or re-engineered technology requires would require a delay for standardization, and avionics production.

Our Assumption is that:

> Over time, some traditional ground navigation aids may be significantly reduced in number while others may have coverage maintained or slightly expanded. At worst, a reduced network will provide some degree of navigational support for most current avionics through 2025.

The long term backup solution avionics need to be available by the year **2010**.	☐ equally important ☐ moderately ☐ strongly ☐ very Strongly	☐ < equal > ☐ more important ☐ less important	The long term backup solution avionics need to be available by the year **2015**.
The long term backup solution avionics need to be available by the year **2010**.	☐ equally important ☐ moderately ☐ strongly ☐ very Strongly	☐ < equal > ☐ more important ☐ less important	The long term backup solution avionics need to be available by the year **2020**.
The long term backup solution avionics need to be available by the year **2015**.	☐ equally important ☐ moderately ☐ strongly ☐ very Strongly	☐ < equal > ☐ more important ☐ less important	The long term backup solution avionics need to be available by the year **2020**.

Main Questionnaire Section: Key Decision Factors

Thank you, we are now ready to get what is the last set of comparisons. Here we will compare what we consider the seven key decision factors in determining a SatNav Backup solution, and would want you to compare them for relative importance.

The factors are:

Low Life Cycle Costs

This factor values low life cycle costs to the users and the infrastructure provider to provide and maintain a SatNav Backup System.

Long term Flexibility:

This factor values that the solution should be flexible in adapting to changing needs without significant reinvestments. For example, the SatNav backup should easily accommodate evolutionary changes to the performance based navigation requirements. Such requirements, driven by increases in traffic density and decreases in separation distances, could be introduced with minimal additional cost to both infrastructure support and users. Support for non precision approaches could be added to airports without major redesign or expansion of ground aid systems.

Redundant Capability and Minimal Operational Impact

This factor values the navigation capability of the backup that enables near equivalent navigation performance as with the primary Satellite Navigation, and also that when required, the transition to the backup (failover) is seamless, with no exceptional crew or ground actions required.

Early Avionics Availability

This factor values the early availability of avionics for the SatNav Backup. We assume that other backup solutions using traditional navigation aids would support the needs of users until the proposed backup avionics are available.

Global Harmonization

This factor values the support of a determined SatNav backup beyond the US or Europe. Full global harmonization requires international standards. Participating regions must commit to necessary investments to build and operate required ground aids.

Spectral Efficiency

This factor values the efficient use of aeronautical radio spectrum, allocation scarce resource to important future aviation voice and data needs.

Additional Key Infrastructure Protection

This factor values that the SatNav backup system would also benefit other key aviation and national infrastructure Position, Navigation, and Timing (PNT) requirements.
(The distribution of precise timing information is critical to sustaining many requirements including future aviation data link communications, aviation surveillance, and the whole national telecommunications infrastructure.)

Key Decision Factor Comparison

Low Life Cycle Cost	☐ equally important ☐ moderately ☐ strongly ☐ very Strongly	☐ < equal > ☐ more important ☐ less important	**Redundant Capability and minimal Operational Impact**
Low Life Cycle Cost	☐ equally important ☐ moderately ☐ strongly ☐ very Strongly	☐ < equal > ☐ more important ☐ less important	**Long term Flexibility**
Low Life Cycle Cost	☐ equally important ☐ moderately ☐ strongly ☐ very Strongly	☐ < equal > ☐ more important ☐ less important	**Early Avionics Availability**
Low Life Cycle Cost	☐ equally important ☐ moderately ☐ strongly ☐ very Strongly	☐ < equal > ☐ more important ☐ less important	**Global harmonization**
Low Life Cycle Cost	☐ equally important ☐ moderately ☐ strongly ☐ very Strongly	☐ < equal > ☐ more important ☐ less important	**Spectral Efficiency**
Low Life Cycle Cost	☐ equally important ☐ moderately ☐ strongly ☐ very Strongly	☐ < equal > ☐ more important ☐ less important	**Additional Key Infrastructure Protection**

Redundant Capability and minimal Operational Impact	☐ equally important ☐ moderately ☐ strongly ☐ very Strongly	☐ < equal > ☐ more important ☐ less important	**Long term Flexibility**
Redundant Capability and minimal Operational Impact	☐ equally important ☐ moderately ☐ strongly ☐ very Strongly	☐ < equal > ☐ more important ☐ less important	**Early Commercial, Certified Avionics Availability**
Redundant Capability and minimal Operational Impact	☐ equally important ☐ moderately ☐ strongly ☐ very Strongly	☐ < equal > ☐ more important ☐ less important	**Global harmonization**
Redundant Capability and minimal Operational Impact	☐ equally important ☐ moderately ☐ strongly ☐ very Strongly	☐ < equal > ☐ more important ☐ less important	**Spectral Efficiency**
Redundant Capability and minimal Operational Impact	☐ equally important ☐ moderately ☐ strongly ☐ very Strongly	☐ < equal > ☐ more important ☐ less important	**Additional Key Infrastructure Protection**

Long term Flexibility	☐ equally important ☐ moderately ☐ strongly ☐ very Strongly	☐ < equal > ☐ more important ☐ less important	**Early Avionics Availability**
Long term Flexibility	☐ equally important ☐ moderately ☐ strongly ☐ very Strongly	☐ < equal > ☐ more important ☐ less important	**Global harmonization**
Long term Flexibility	☐ equally important ☐ moderately ☐ strongly ☐ very Strongly	☐ < equal > ☐ more important ☐ less important	**Spectral Efficiency**
Long term Flexibility	☐ equally important ☐ moderately ☐ strongly ☐ very Strongly	☐ < equal > ☐ more important ☐ less important	**Additional Key Infrastructure Protection**

Early Avionics Availability	☐ equally important ☐ moderately ☐ strongly ☐ very Strongly	☐ < equal > ☐ more important ☐ less important	**Global harmonization**
Early Avionics Availability	☐ equally important ☐ moderately ☐ strongly ☐ very Strongly	☐ < equal > ☐ more important ☐ less important	**Spectral Efficiency**
Early Avionics Availability	☐ equally important ☐ moderately ☐ strongly ☐ very Strongly	☐ < equal > ☐ more important ☐ less important	**Additional Key Infrastructure Protection**

Global harmonization	☐ equally important ☐ moderately ☐ strongly ☐ very Strongly	☐ < equal > ☐ more important ☐ less important	**Spectral Efficiency**
Global harmonization	☐ equally important ☐ moderately ☐ strongly ☐ very Strongly	☐ < equal > ☐ more important ☐ less important	**Additional Key Infrastructure Protection**

Spectral Efficiency	☐ equally important ☐ moderately ☐ strongly ☐ very Strongly	☐ < equal > ☐ more important ☐ less important	**Additional Key Infrastructure Protection**

APPENDIX F. LIST OF ACRONYMS & ABBREVIATIONS

The following list identifies acronyms and abbreviations used throughout this report.

$ K	$1,000
$ M	$1,000,000
4D	Four-Dimensional
AC	Air Carrier
ADS-B	Automatic Dependent Surveillance Broadcast
ADS-R	Automatic Dependent Surveillance Rebroadcast
AHP	Analytical Hierarchy Process
AOC	Air Operations Center
AOPA	Aircraft Owners and Pilots Association
ASICs	Application Specific Integrated Circuits
ATA	Air Transport Association
ATC	Air Traffic Control
ATM	Air Traffic Management
ATN	Aeronautical Telecommunications Network
ATS	Air Traffic Services
CAA	Civil Aviation Authority
CAT I, II, III	Categories for Precision Approaches
CDMA	Code Division Multiple Access
COI	Community of Interest
CONUS	Contiguous United States region
DME	Distance Measuring Equipment
DME/DME	Denotes the capability to determine position relative to multiple DME stations
DoC	U.S. Department of Commerce
DoD	U.S. Department of Defense
DoT	U.S. Department of Transportation
ECAC	European Civil Aviation Conference
EGNOS	European Geostationary Navigation Overlay Service
eLORAN	Enhanced LORAN
EPU	Estimated Position Uncertainty
EU	European Union
EUROCONTROL	European Organisation for the Safety of Air Navigation
EVS	Enhanced Vision System
FAA	Federal Aviation Administration
FANS	Future Air Navigation System
FCC	Federal Communications Commission
FDMA	Frequency Division Multiple Access
FHWA	Federal Highway Administration
FIS-B	Flight Information Services- Broadcast
FMS	Flight Management System
FRP	Federal Radionavigation Plan
GA	General Aviation
GBAS	Ground Based Augmentation System
GHz	Gigahertz
GLONASS	Russian Global Navigation Satellite System
GNSS	Global Navigation Satellite System

GPS	(U.S.) Global Positioning System
HMI	Hazardously Misleading Information
HPL	Horizontal Protection Limit
HS	U.S. Department of Homeland Security
IAP	Instrument Approach Procedure
ICAO	International Civil Aviation Organization
ILS	Instrument Landing System
INS	Inertial Navigation System
IRS	Inertial Reference System
IRU	Inertial Reference Unit
ITS	Intelligent Transportation System
JPDO	Joint Planning and Decision Office
KHz	Kilohertz
KW	Kilowatt
LAAS	Local Area Augmentation System
LF	Low Frequency
LIDAR	LIght Detection and Ranging
LORAN	Long Range Navigation
LORAN-C	LORAN performance and operational specification being replaced by eLORAN
LPV	Localizer Performance with Vertical Guidance
M. m	meter
MASPS	Minimum Aviation System Performance Standards
MLS	Microwave Landing System
MOPS	Minimum Operational Performance Standards
NAC_p	Navigation Accuracy Category for Position
NAS	National Airspace System
NDB	Non Directional Beacon
NextGen	Next Generation Air Transportation System
NGATS	Next Generation Air Transportation System
NIC	Navigation Integrity Category
NM, nm	Nautical Mile
NPA	Non Precision Approach
NPV	Net Present Value
NSSO	National Space and Security Office
O&M	Operation and Maintenance (Cost)
OEP	Operation Evolution Plan
PNT	Position, Navigation, and Timing
PTAN	Precision Terrain Navigation System
RAIM	Receiver Autonomous Integrity Monitor
RITA	(DoT) Research and Innovative Technology Administration
RNAV	Area Navigation
RNP	Required Navigational Performance
ROM	Rough Order of Magnitude (estimate)
RTCA	Radio Technical Commission for Aeronautics
SARPS	Standards and Recommended Practices
SatNav	Satellite Based Navigation
SBAS	Space Based Augmentation System
SESAR	Single European Sky ATM Research
SID	Standard Instrument Departure
SOW	Statement of Work

SSA	Shared Situational Awareness
SSR	Secondary Surveillance Radar
STAR	Standard Terminal Arrival
TACAN	Tactical Air Navigation
TDOA	Time Distance of Arrival
TIS-B	Traffic Information Services- Broadcast
TRN	Terrain Reference Navigation
U.S.	United States of America
VEPU	Vertical Error Position Uncertainty
VHF	Very High Frequency
VOC	Voice of the Customer
VOR	VHF Omni Directional Range
VOR/DME	Collocated VOR and DME navigation aids
VORTAC	Collocated VOR and TACAN navigation aids
WAAS	Wide Area Augmentation System
WAM	Wide Area Multilateration

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